

AF-Shell: AN ENRICHED FINITE ELEMENT FOR EFFICIENT DAMAGE SIMULATION IN COMPOSITE LAMINATES

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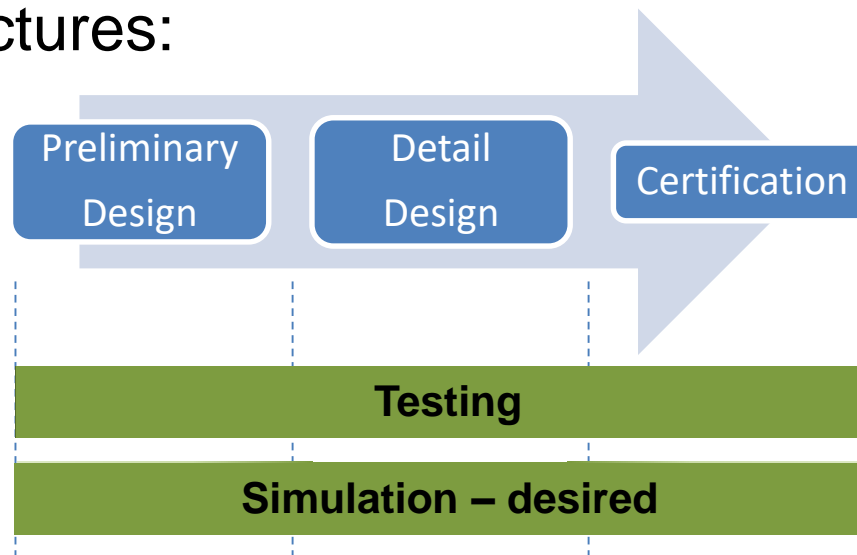
- Motivation and Approach
- Model Overview
- Initial Verification and Validation
- Ongoing Work
- Concluding Remarks

Motivation and Approach



Design and certification process for composite aerospace structures:

- Heavily reliant on tests
- Expensive
- Simulation tools may reduce the need for some testing



→ Approach: Enriched shell element model for progressive damage simulation

- Adaptive Fidelity Shell (AFS)
- Computationally efficient
- Rapid design tool

Motivation and Approach

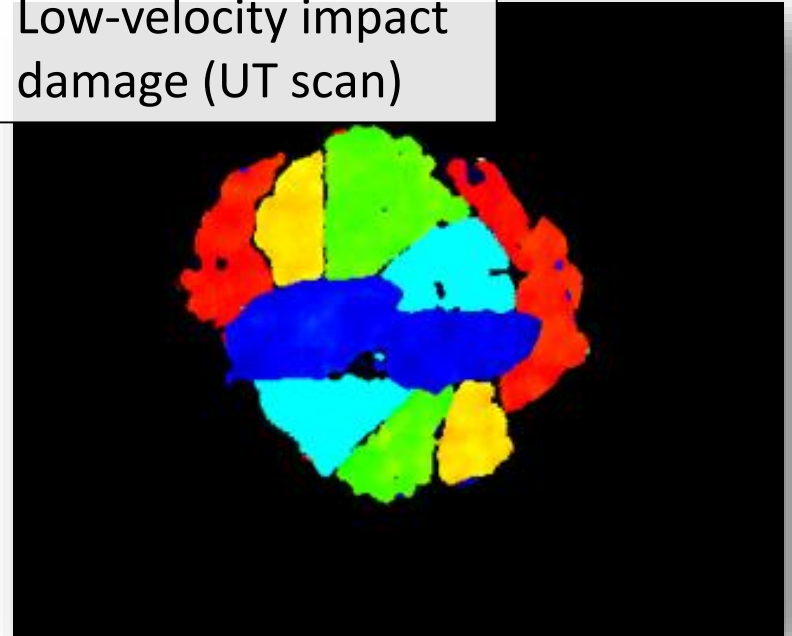


Progressive damage in composite laminates:

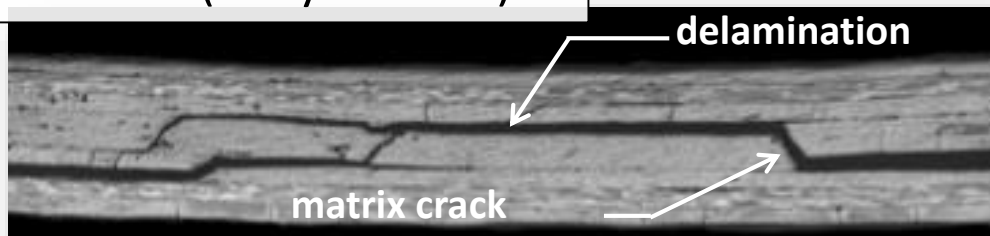
Delamination



Low-velocity impact damage (UT scan)



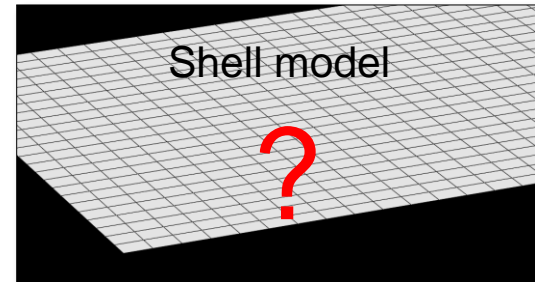
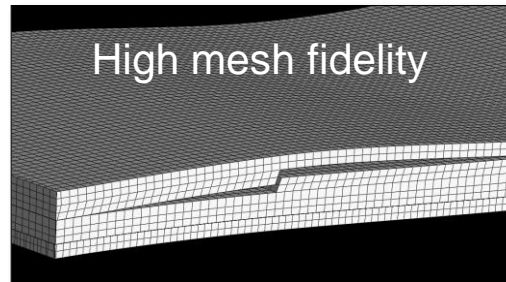
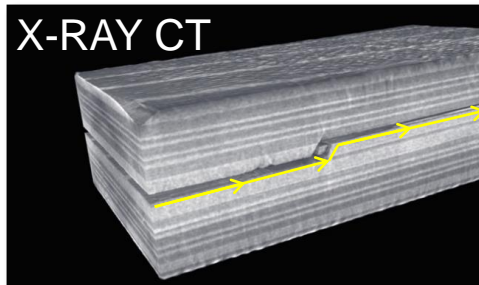
Delamination-matrix crack interaction (X ray CT scan)



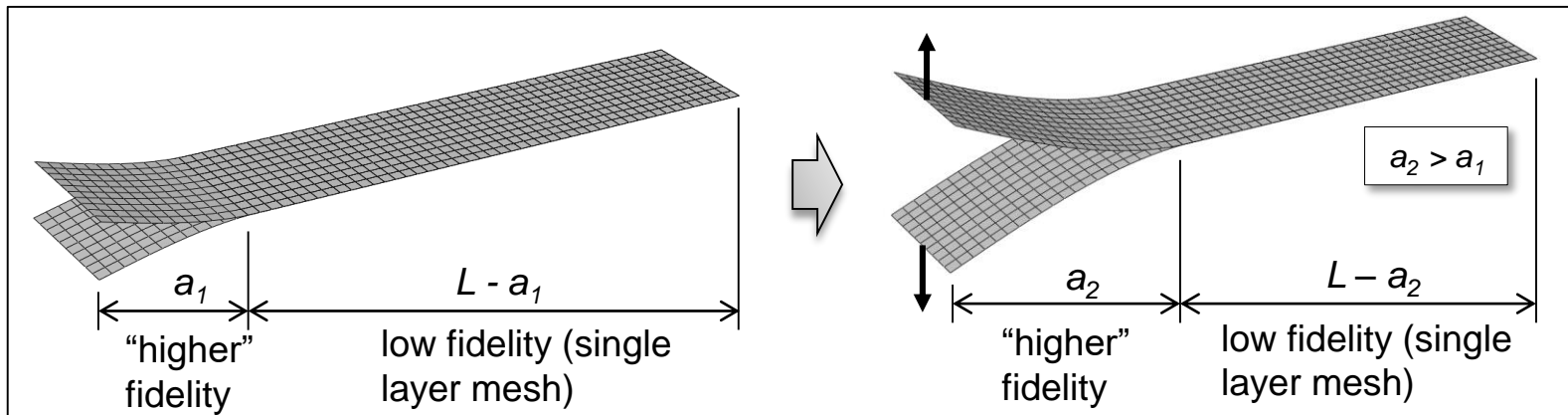
Model Overview



- Computationally efficient & user friendly → shell method requires fundamentally new approach
- Progressive damage simulation: delamination-matrix crack interaction



- Adaptive fidelity

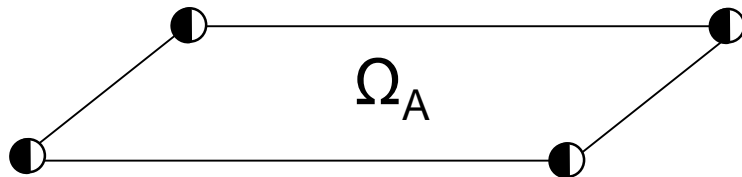


Model Overview: Floating Node Method*

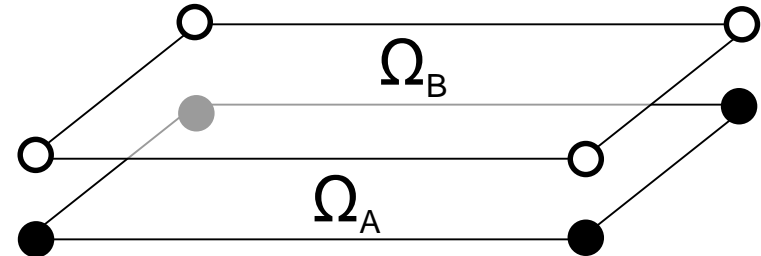


Shell element enrichment to allow adaptive mesh fidelity

Undamaged Element



Split Element



$$K^{(e)} = \begin{bmatrix} [K_{\Omega_A}^{(e)}]_{24 \times 24} & [0] \\ [0] & [0]_{24 \times 24} \end{bmatrix}_{48 \times 48}$$

$$K^{(e)} = \begin{bmatrix} [K_{\Omega_A}^{(e)}]_{24 \times 24} & [0] \\ [0] & [K_{\Omega_B}^{(e)}]_{24 \times 24} \end{bmatrix}_{48 \times 48}$$

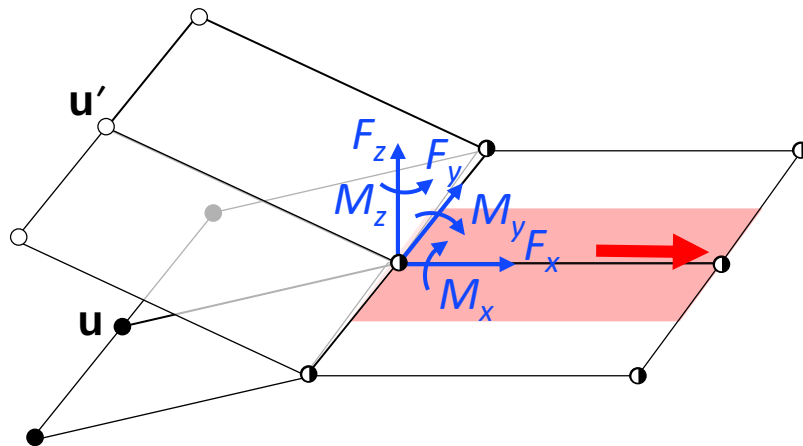
○ = floating node (FN) ● = real node (RN) ◐ = RN and unused FN

*Chen, B.Y., Pinho, S.T., De Carvalho N.V., Baiz, P.M., Tay, T.E. 2014. "A Floating Node Method for the Modelling of Discontinuities in Composites," *Engineering Fracture Mechanics* 127:104-134.

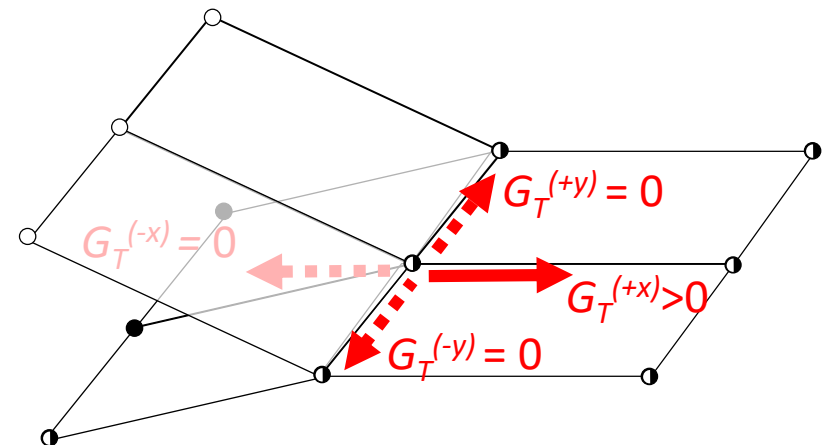
Model Overview: Delamination Propagation



Virtual Crack Closure Technique (VCCT)



VCCT in AFS model: G_T calculated for delamination growth in 4 directions



○ = floating node (FN)

● = real node (RN)

⦿ = coincident RN and FN

■ = change in delamination area if tie is released (ΔA)

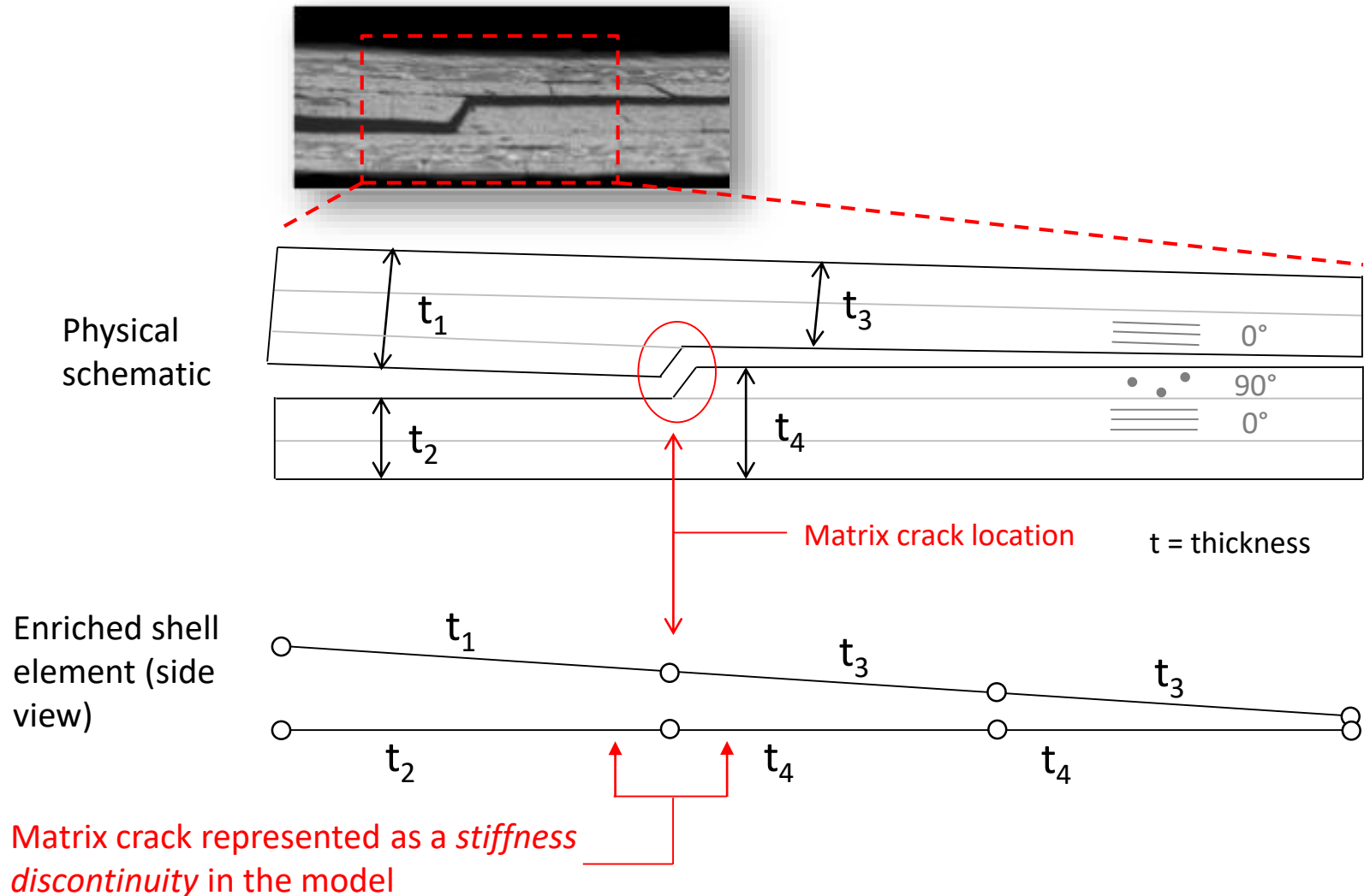
➔ = growth direction

If $G_T > G_c$ in any direction, tie is released

Model Overview: Transverse Cracks



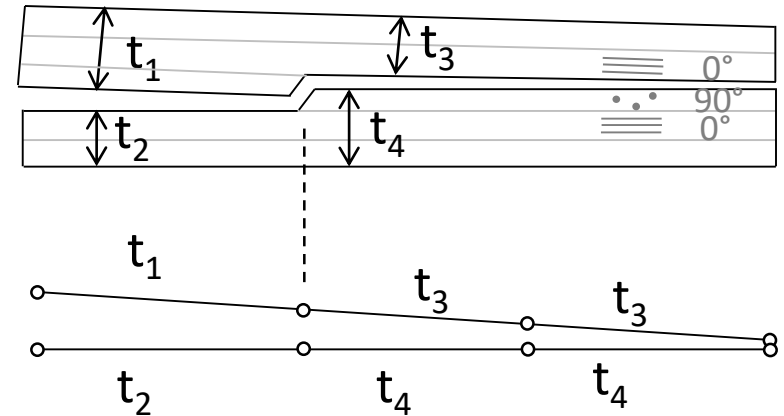
Representing transverse cracks: delamination-migration



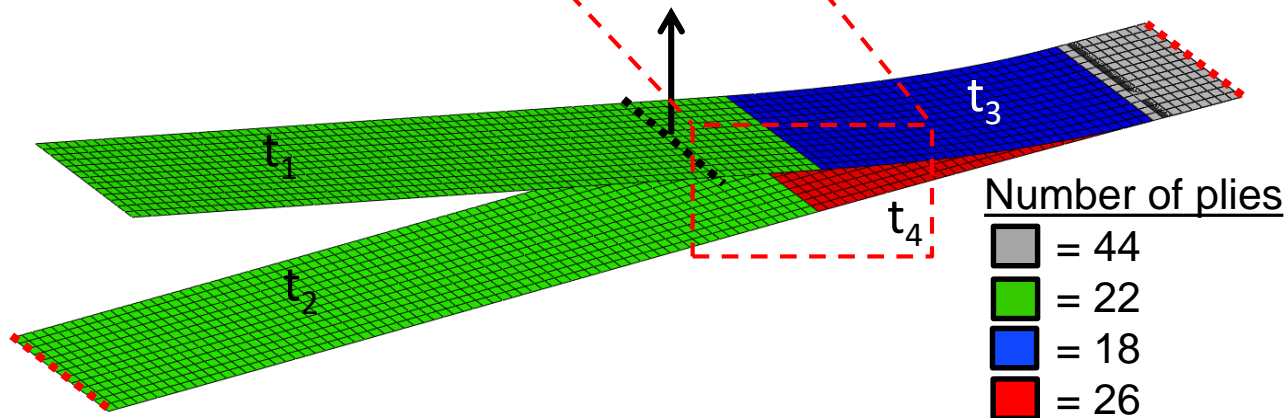
Model Overview: Transverse Cracks



Example: delamination-migration

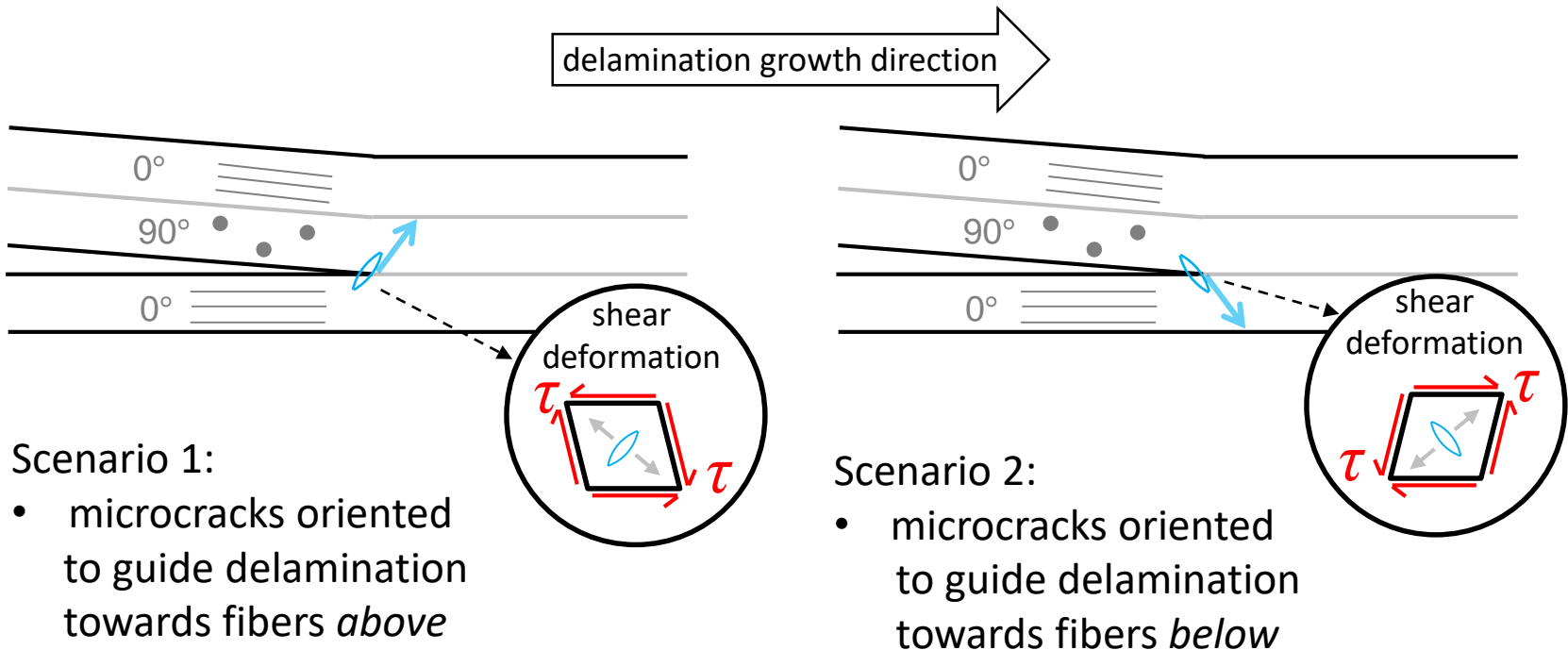


AF-Shell model:



Predicting Transverse Cracks

Step I: Use shear sign to determine transverse delamination growth tendency



= transverse delamination growth tendency

= microcracks preceding delamination

Predicting Transverse Cracks

Step II: Energy criterion

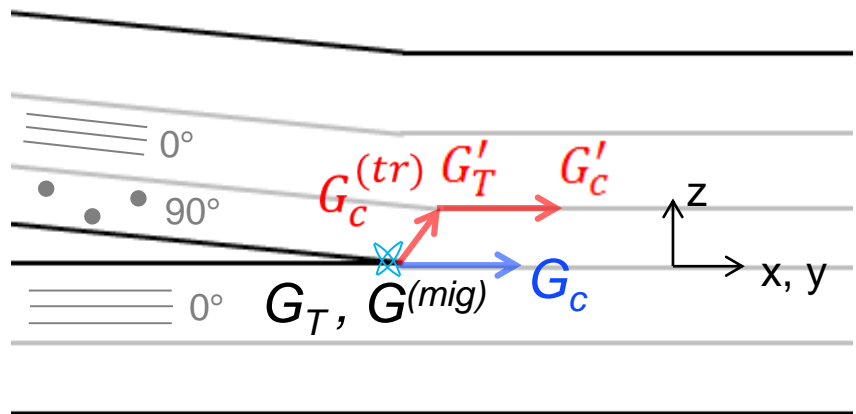
Three possibilities:

$$G_T < G_c \rightarrow \text{No growth}$$

$$\left. \begin{array}{l} G_T > G_c \\ \& \\ G^{(mig)} < G_c^{(tr)} \end{array} \right\} \rightarrow \text{Delamination, no migration}$$

$$\left. \begin{array}{l} G_T > G_c \\ \& \\ G^{(mig)} > G_c^{(tr)} \end{array} \right\} \rightarrow \text{Delamination \& migration}$$

$$\text{Assumptions} \left\{ \begin{array}{l} G'_T \cong G_T \\ \Delta U_{mig} \ll \Delta U_{delam} \end{array} \right.$$



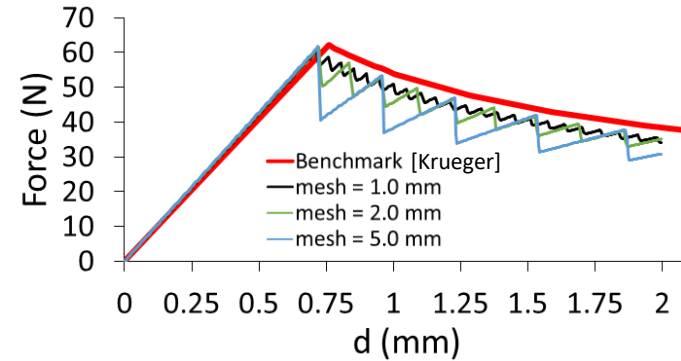
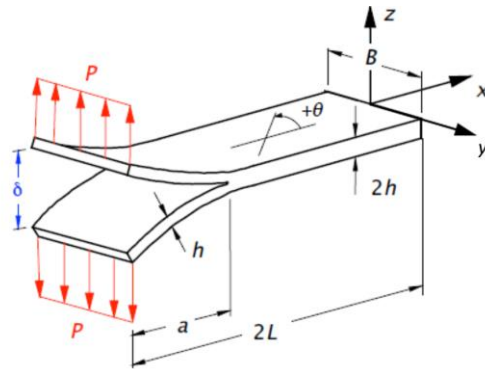
$$\begin{aligned} G_c^{(90^\circ)} &= G_{Ic}^{(matrix)} \\ G_c^{(0^\circ)} &= \infty \end{aligned}$$

$$G^{(mig)} = ?$$

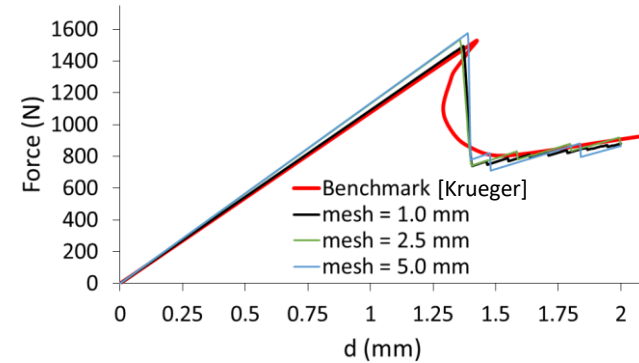
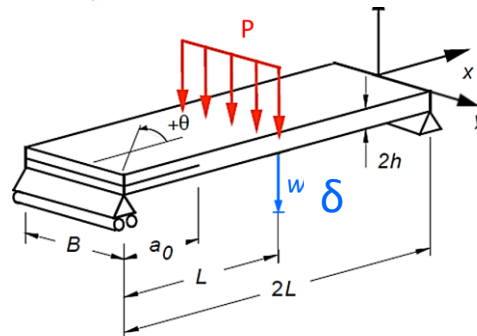
Verification and Validation



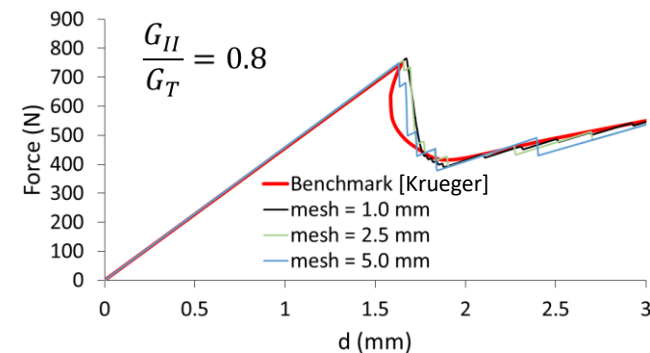
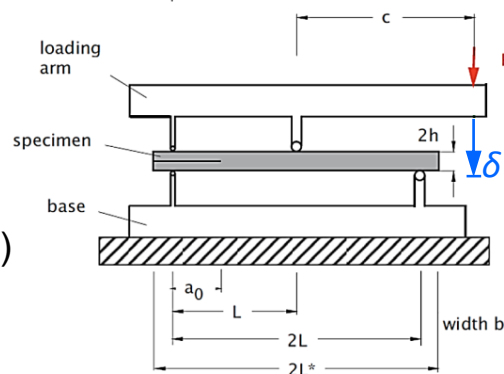
Double
Cantilever
Beam
(Mode I)



End Notch
Flexure
(Mode II)



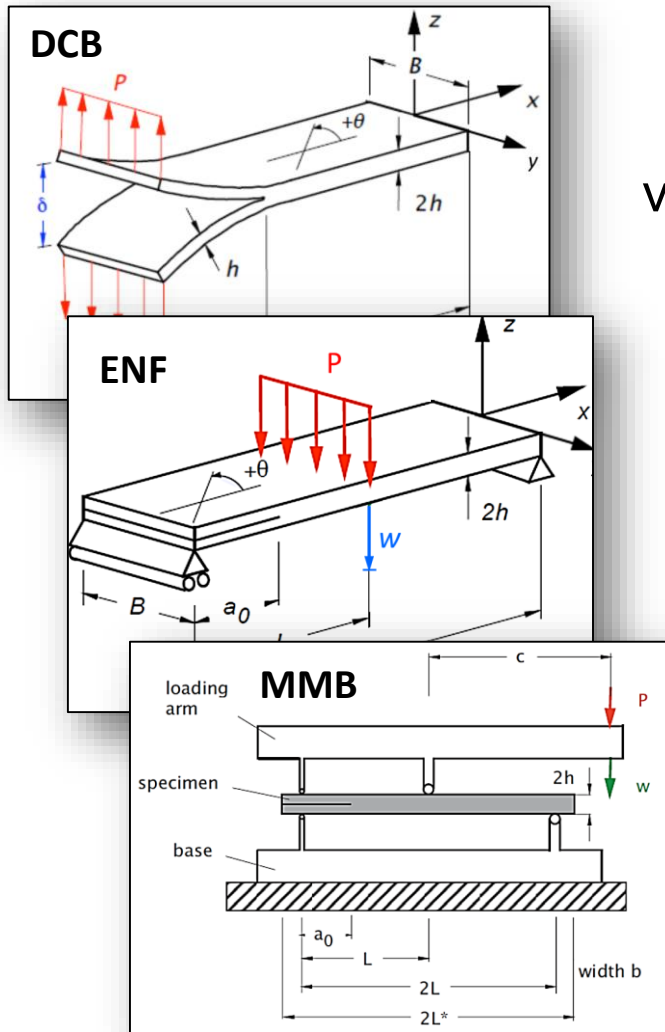
Mixed-mode
Bending
(Mixed-mode I/II)



Verification and Validation



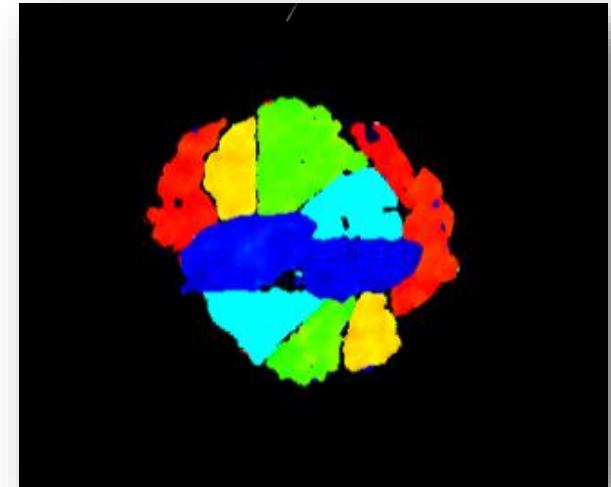
Basic validation data



“medium”
complexity
validation data

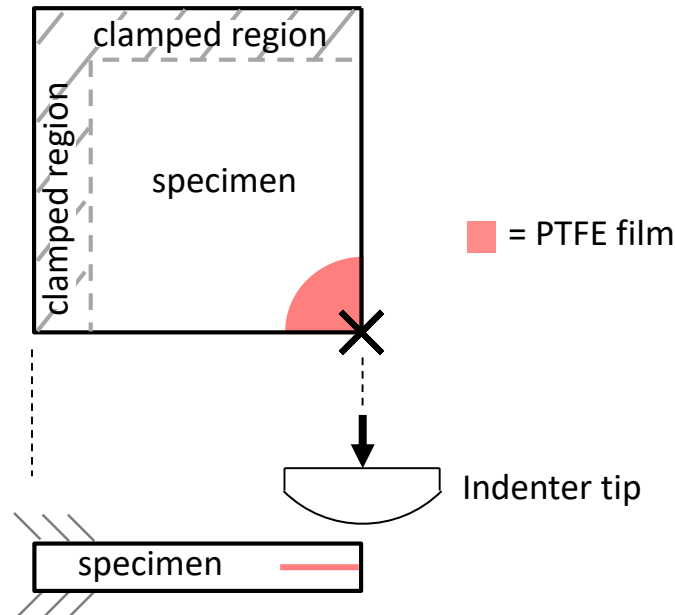


Impact validation data



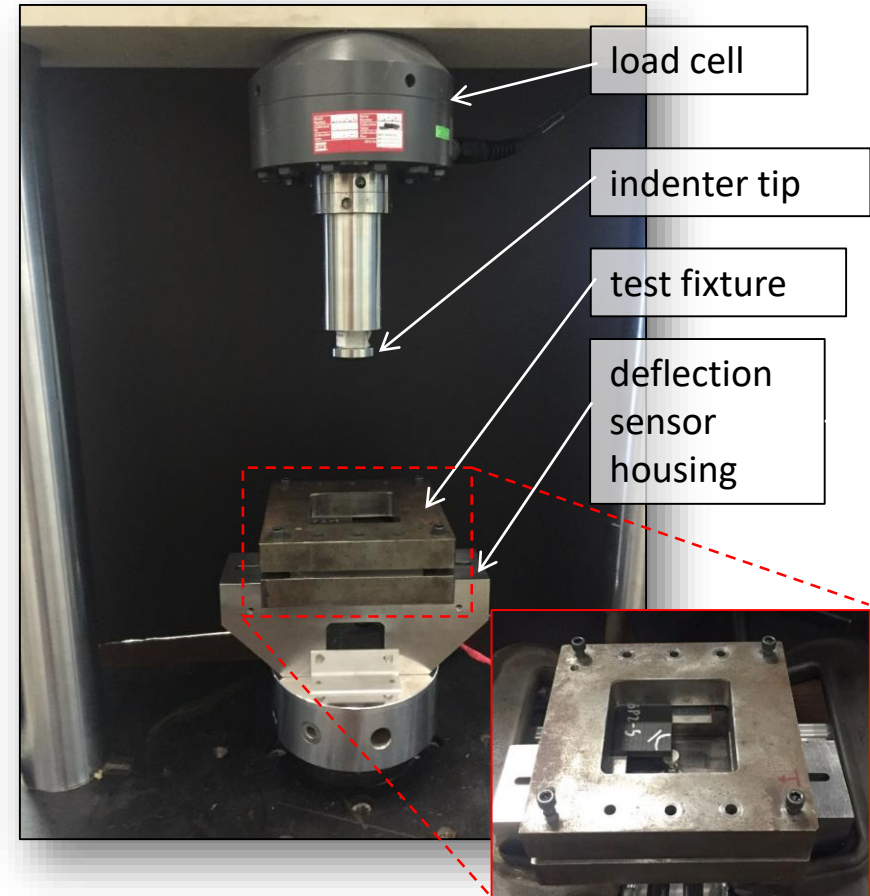
- Primary damage mechanism: growth and interaction of multiple delaminations and matrix cracks
- “medium” complexity → limit damage to 2-3 interfaces

Verification and Validation: Biaxial-Bending Test (BBT)



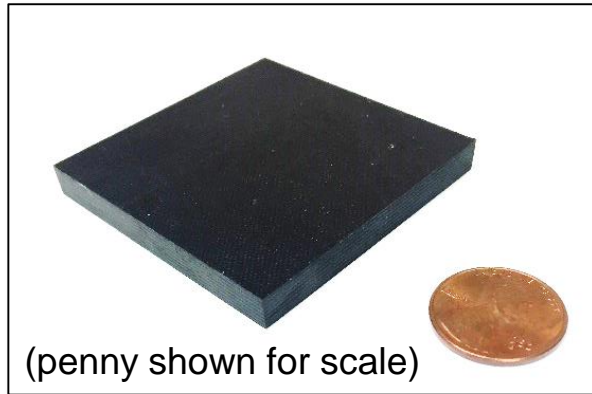
“Quarter plate” design

- 2 free edges on initial delamination
- **Damage limited to delaminations at 2-3 ply interfaces**
- **Stable damage growth**



Note: Similar to Canturri, C, Greenhalgh, ES, Pinho, ST. The relationship between mixed-mode II/III delamination and delamination migration in composite laminates. Composites Science and Technology, 105:102-109, 2014.

Verification and Validation: BBT Specimen

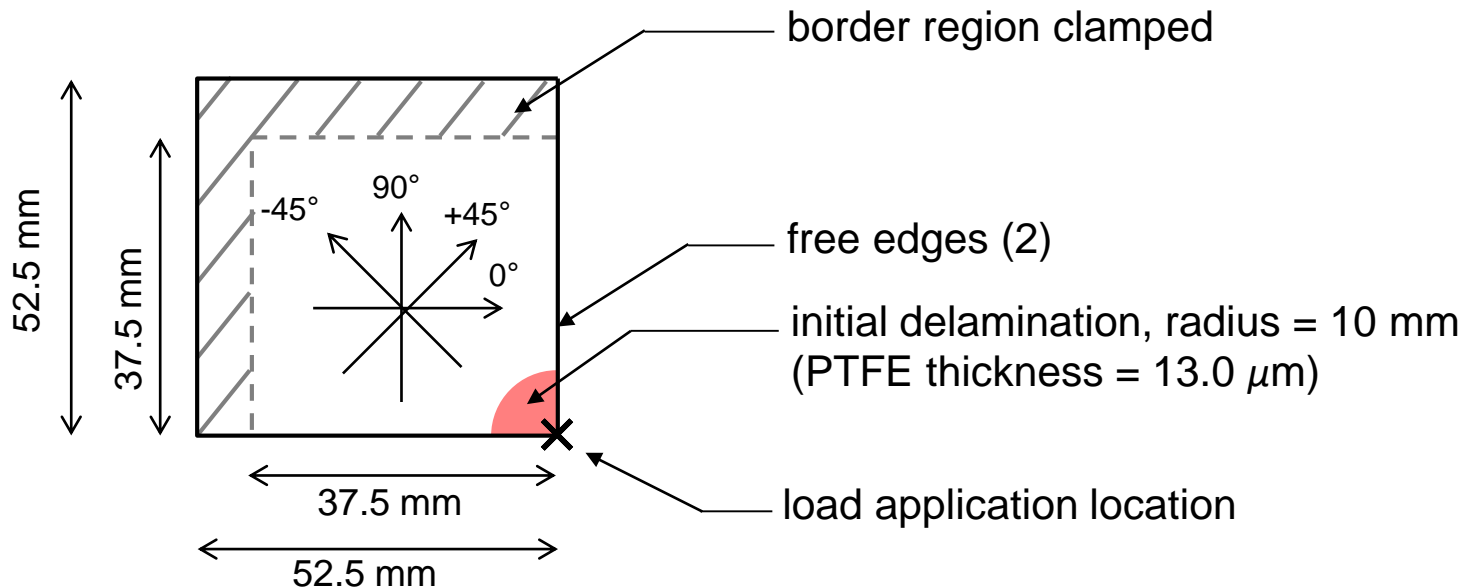


Layup 1: $[(0_2/90_2)_4/0_2/\textcolor{red}{T}/90_2/0_2/(90_2/0_2)_3]$

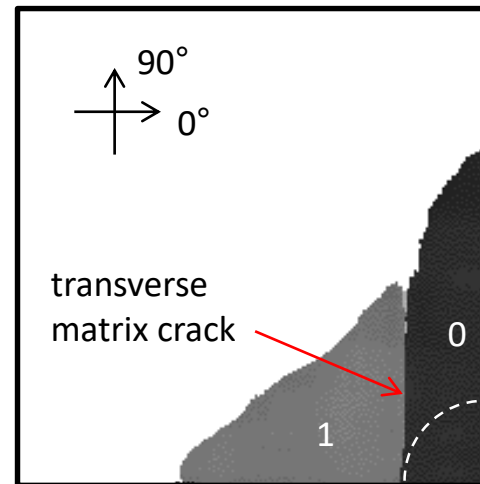
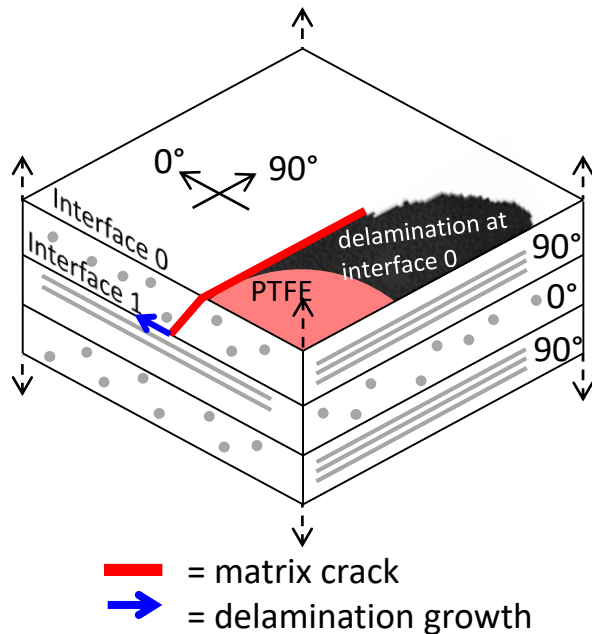
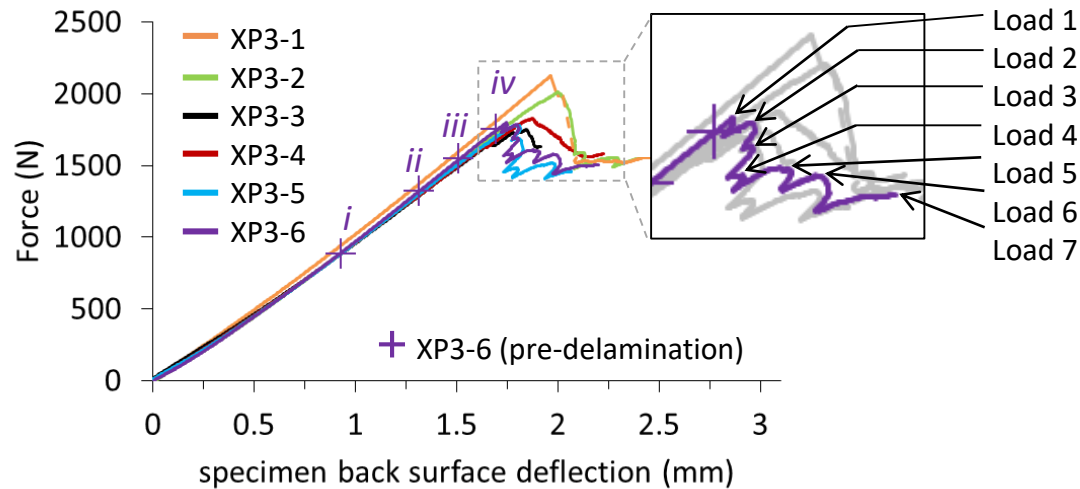
Layup 2: $[(0_2/90_2)_3/0_2/45_2/0_2/\textcolor{red}{T}/-45_2/0_2/(90_2/0_2)_3]$

Layup 3: $[(0_2/90_2)_3/0_2/-45_2/0_2/\textcolor{red}{T}/45_2/0_2/(90_2/0_2)_3]$

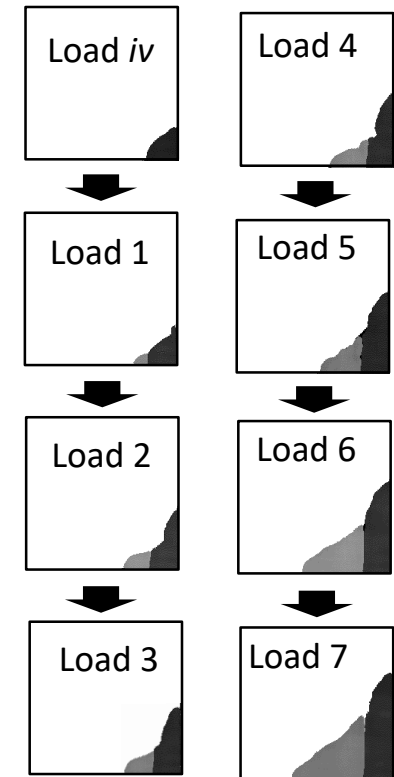
$\textcolor{red}{T}$ = PTFE (Teflon™)



Verification and Validation: BBT-1 Simulation



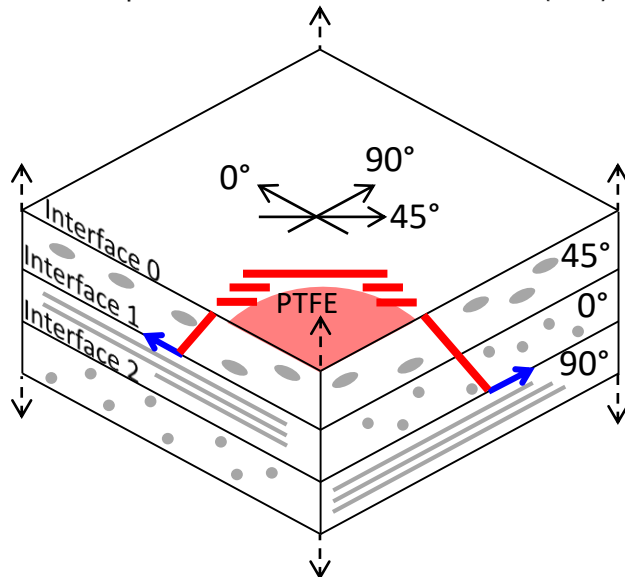
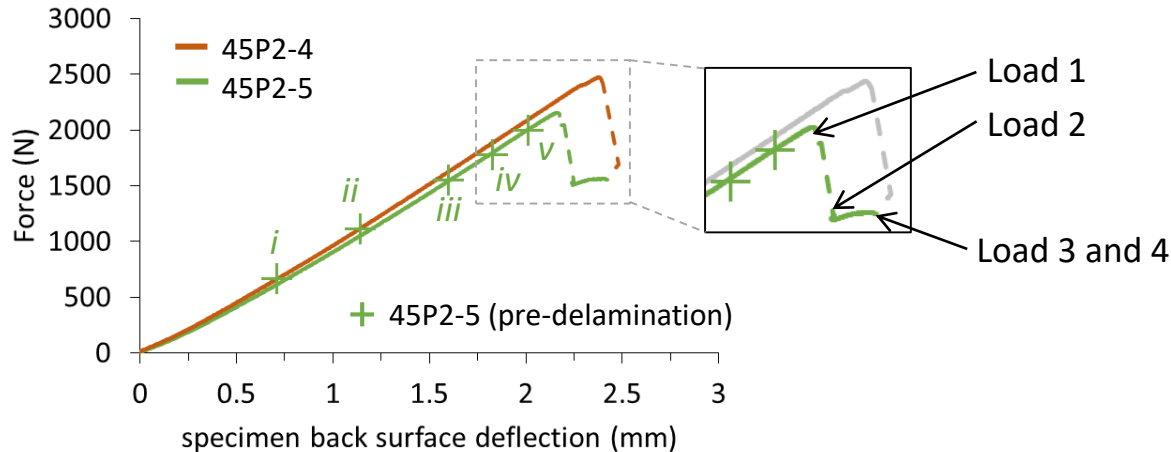
Intermittent damage scans



■ = delamination at interface 0
■ = delamination at interface 1

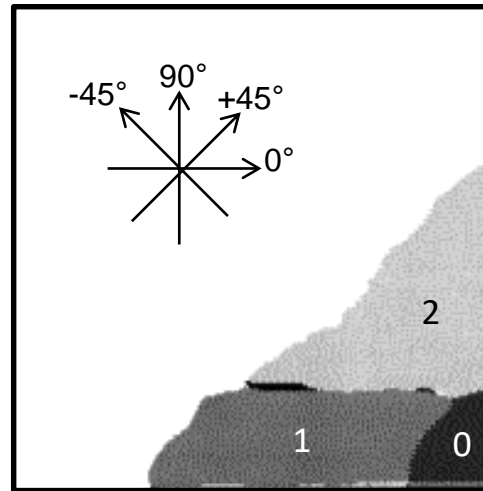
0 1
↓ ↓
[(0₂/90₂)₄/0₂/T/90₂/0₂/(90₂/0₂)₃]

Verification and Validation: BBT-3

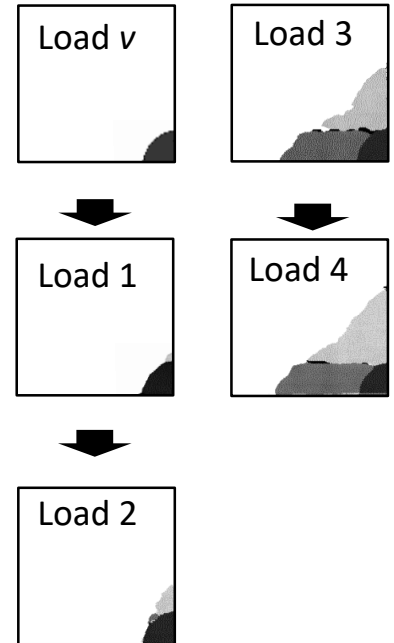


— = matrix crack

→ = delamination growth



Intermittent damage scans



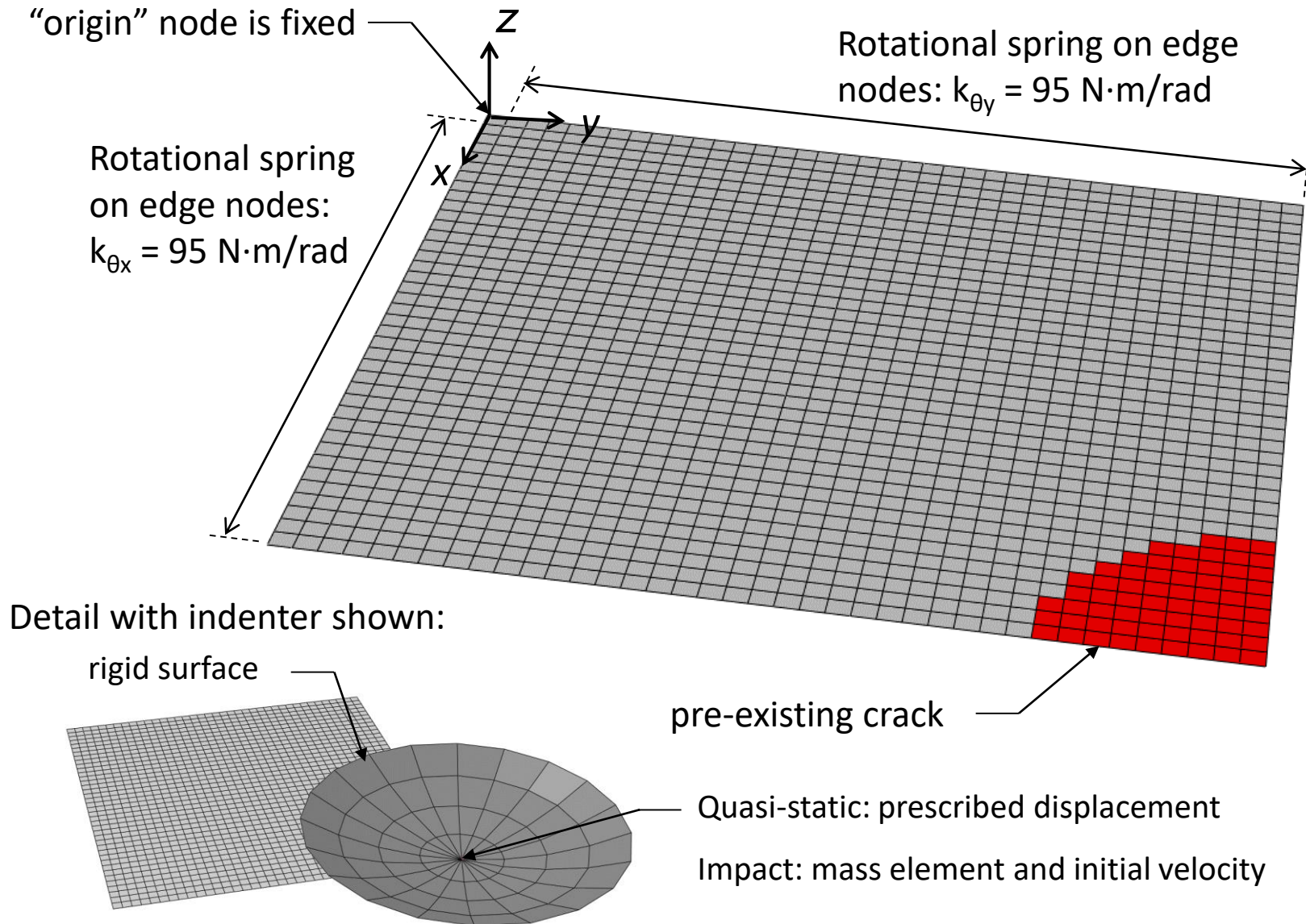
■ = delamination at interface 0

■ = delamination at interface 1

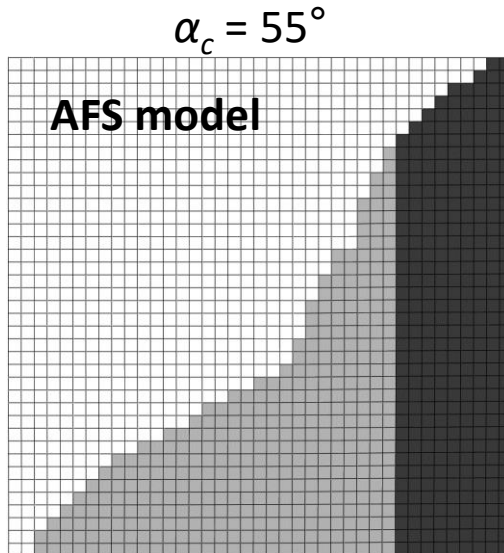
■ = delamination at interface 2

$$[(0_2/90_2)_3/0_2/-45_2/0_2/\overset{\downarrow 0}{\text{T}}/45_2/0_2/(\overset{\downarrow 1}{90_2}/\overset{\downarrow 2}{0_2})_3]$$

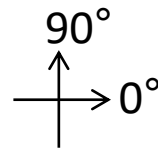
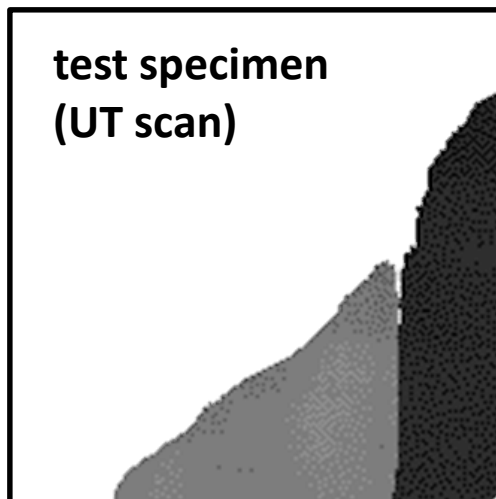
Verification and Validation: BBT Simulation



Verification and Validation: BBT-1 Simulation



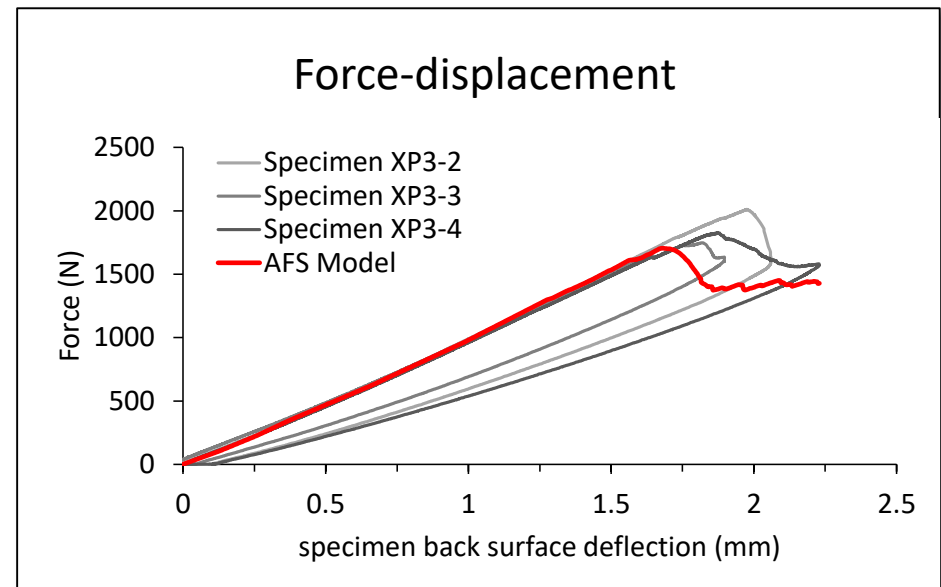
($\delta = 2.18$ mm)



■ = delamination at interface 0

■ = delamination at interface 1

$[(0_2/90_2)_4/0_2/\overset{0}{\text{T}}/90_2/0_2/\overset{1}{(90_2/0_2)_3}]$

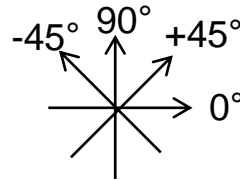
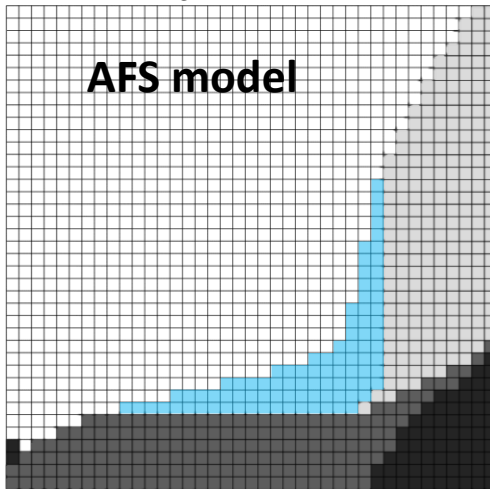






Verification and Validation: BBT-3 Simulation



$\alpha_c = 50^\circ$

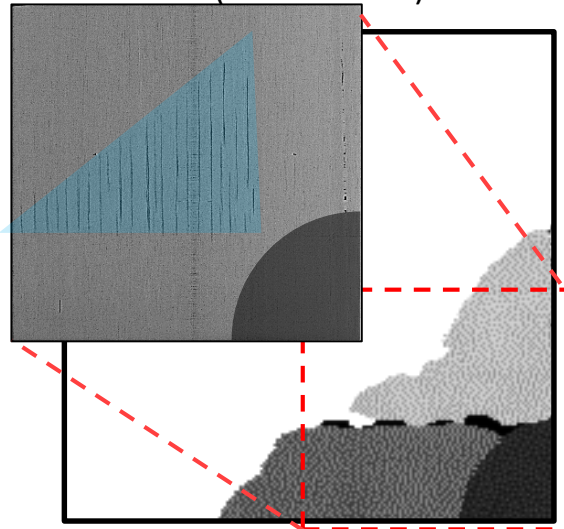
AFS model



-  = delamination at interface 0
-  = delamination at interface 1
-  = delamination at interface 2
-  = delamination at interface 3

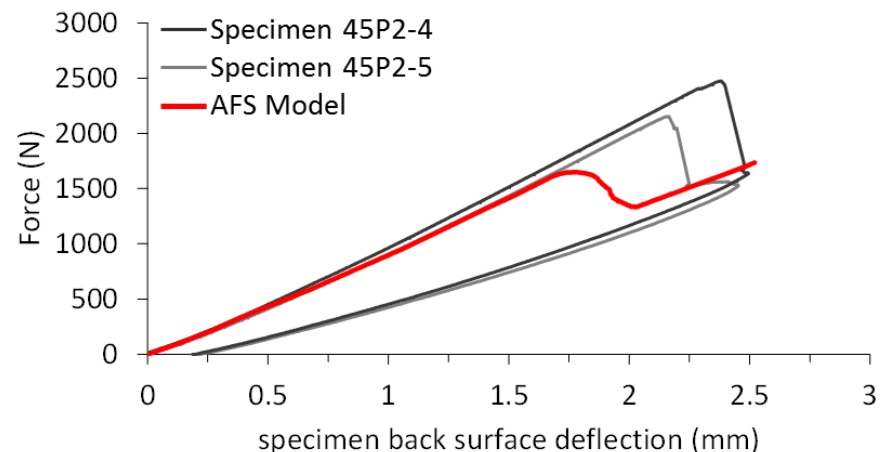
0 1 2 3
↓ ↓ ↓ ↓
[(0₂/90₂)₃/0₂/-45₂/0₂/**T**/45₂/0₂/(90₂/0₂)₃]

($\delta = 2.18$ mm)

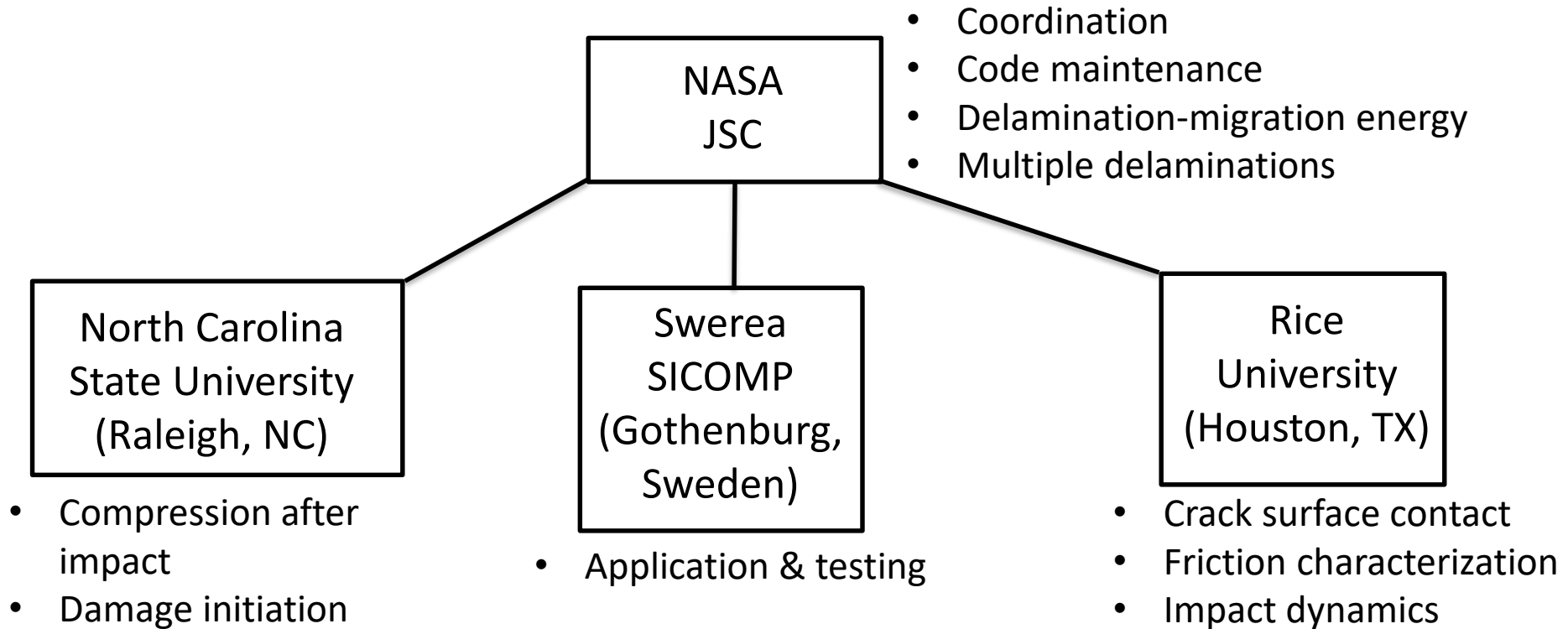


test specimen (UT scan)

Force-displacement



Ongoing Work: Collaboration Structure



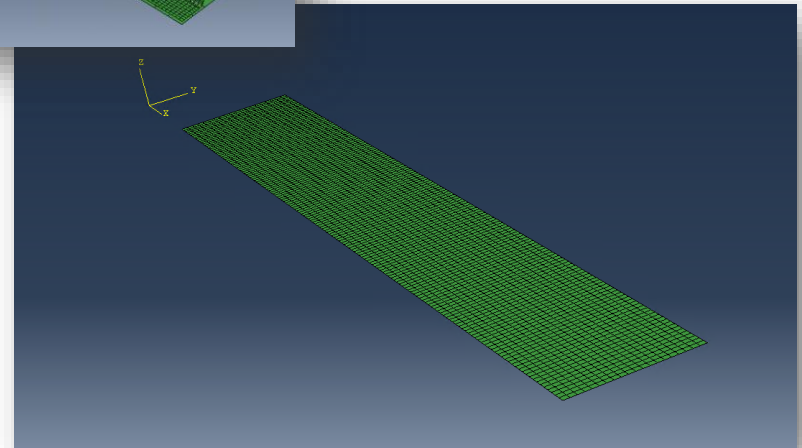
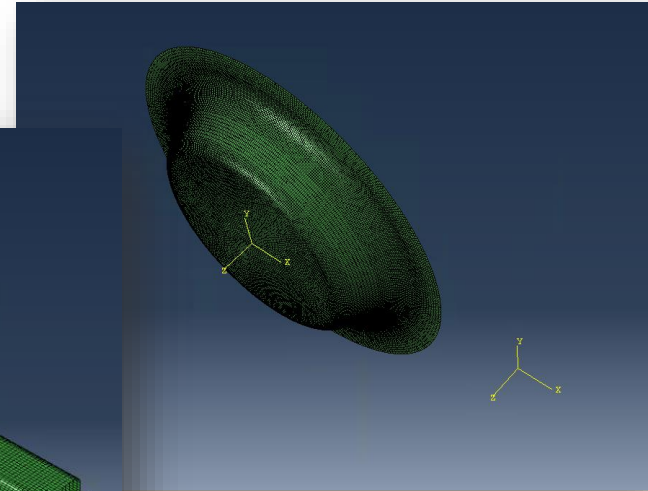
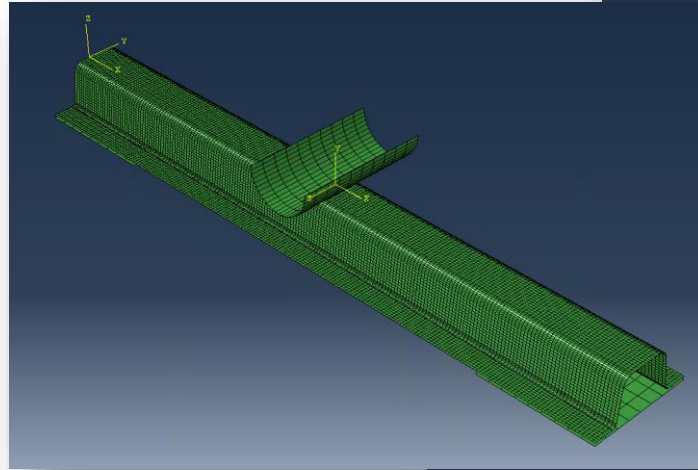
Ongoing Work: Software Application and Testing



Goal: mature AF-Shell from a bespoke research code to a general analysis tool

Approach: apply AF-Shell to existing models

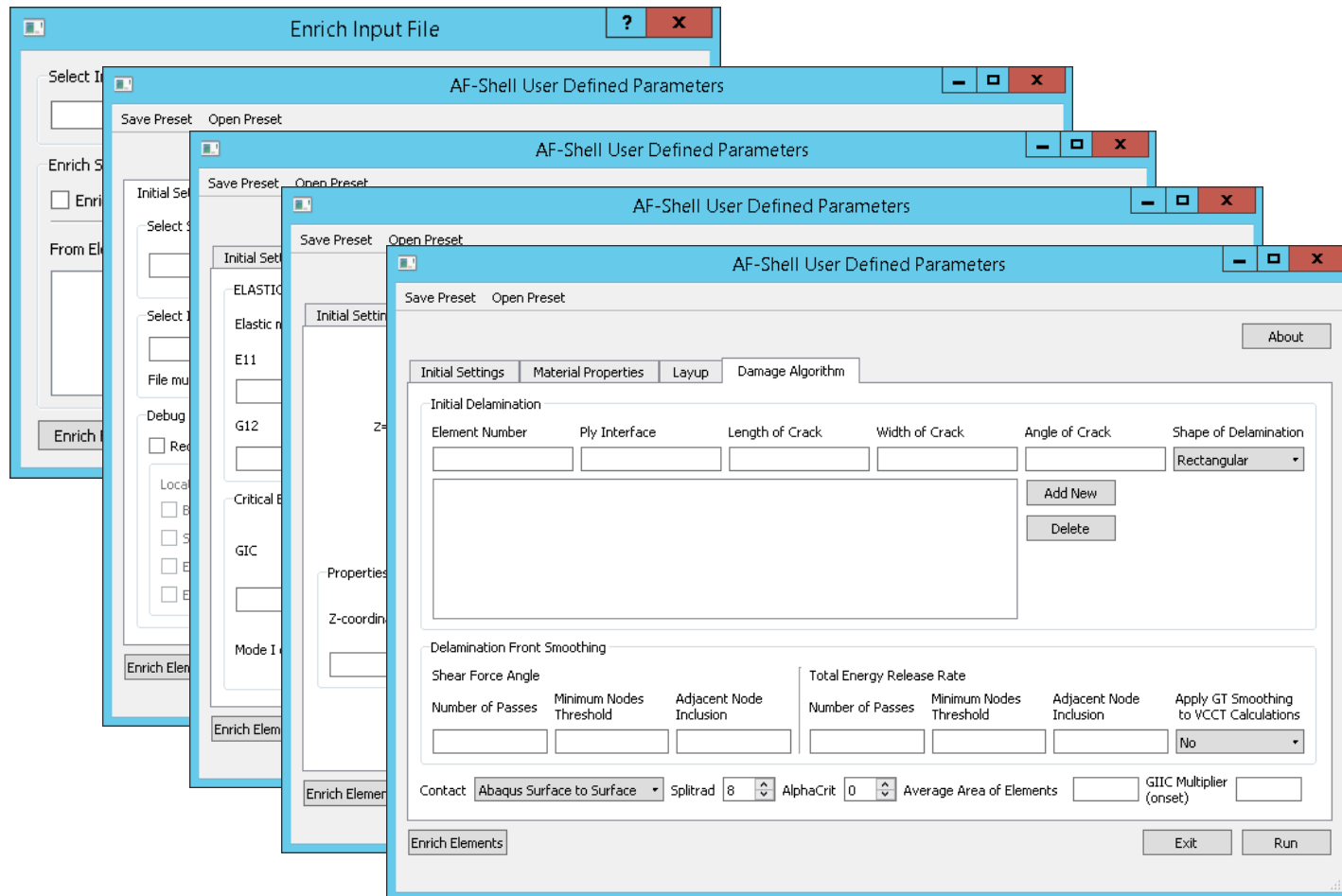
1. Enrich shell elements in existing models
2. Identify bugs and errors
3. Debug and upgrade AF-Shell as needed



Ongoing Work: Graphical User Interface



- Enrich pre-existing model file
- Set up user defined parameters in AF-Shell
- Run analyses

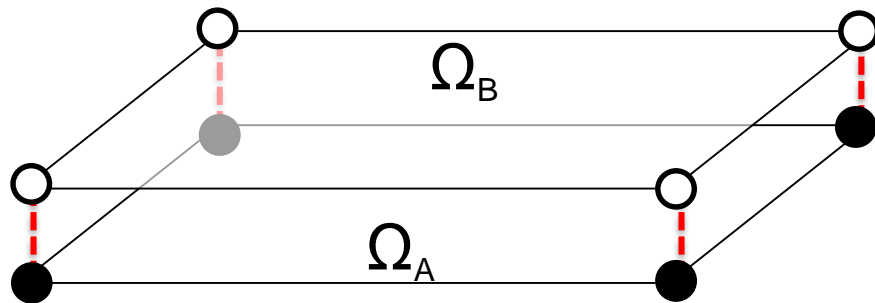


Ongoing Work: Contact

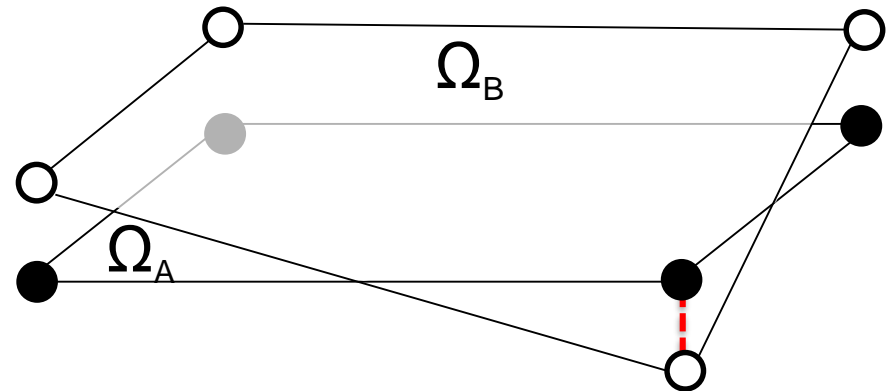


Current “work-around”
contact options in AF-Shell

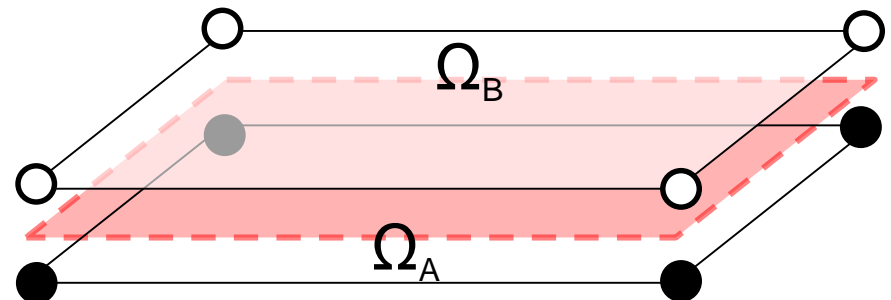
1. Transverse DOF nodal ties



2. Conditional transverse DOF nodal ties



3. Abaqus surface-to-surface contact



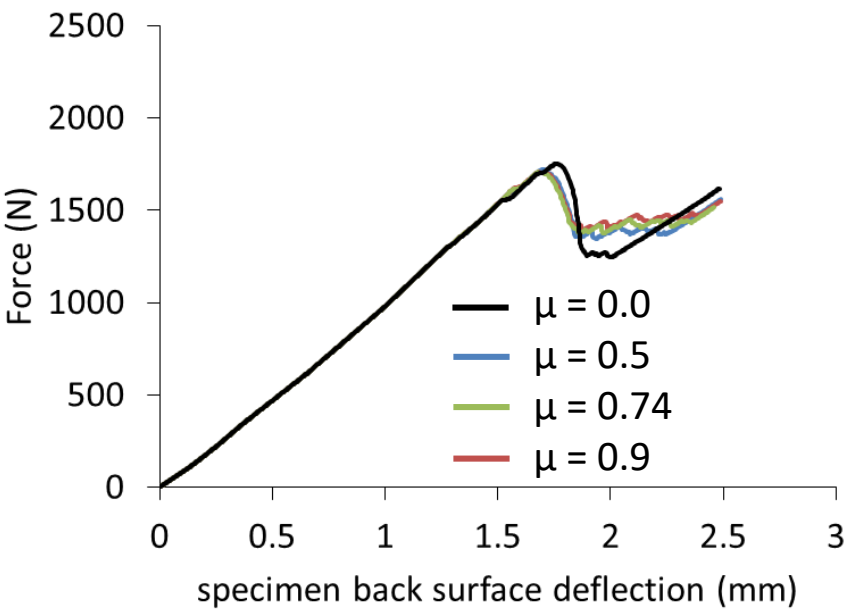
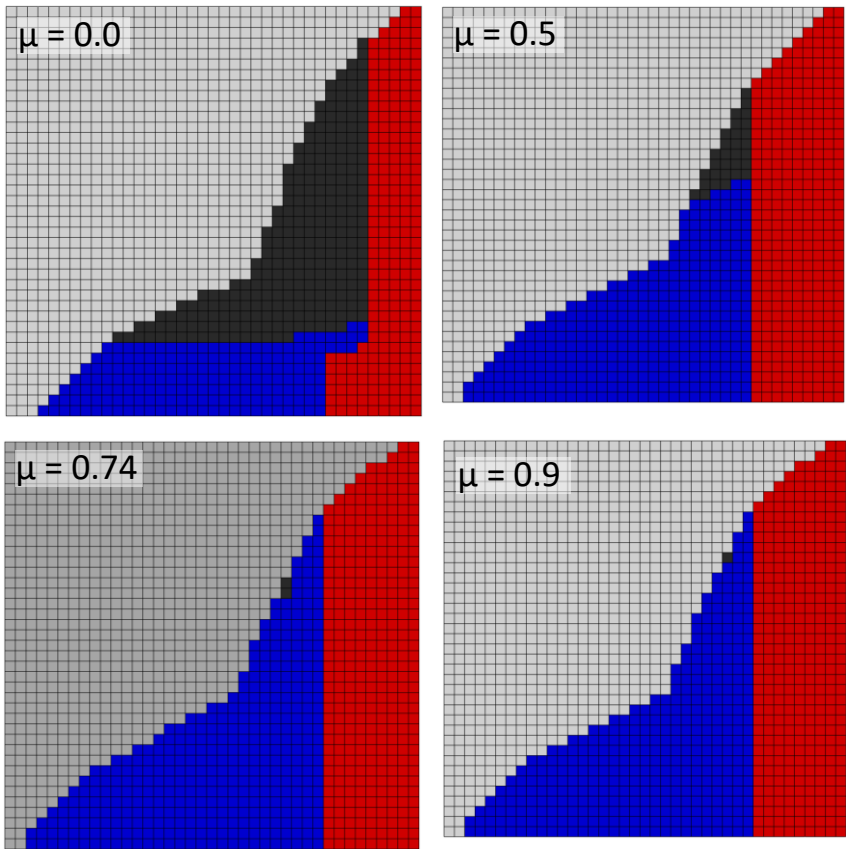
○ = floating node (FN)

● = real node (RN)

Ongoing Work: Contact



Behavioral dependency in model on coefficient of friction:



Layup 1

$\begin{matrix} 0 & 1 & 2 \\ \downarrow & \downarrow & \downarrow \end{matrix}$

$[(0_2/90_2)_4/0_2/\textcolor{red}{T}/90_2/0_2/(90_2/0_2)_3]$

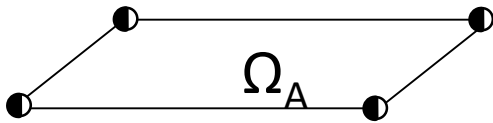
delamination

- interface 0
- interface 1
- interface 2

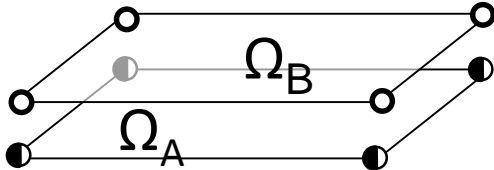
Ongoing Work: Multiple Delaminations



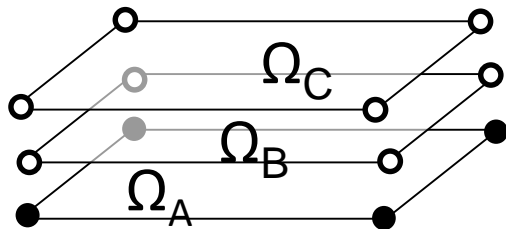
Multiple delaminations using the Floating Node Method



$$K^{(e)} = \begin{bmatrix} [K_{\Omega_A}^{(e)}]_{24 \times 24} & [0] & [0] \\ [0] & [0]_{24 \times 24} & [0] \\ [0] & [0] & [0]_{24 \times 24} \end{bmatrix}_{72 \times 72}$$



$$K^{(e)} = \begin{bmatrix} [K_{\Omega_A}^{(e)}]_{24 \times 24} & [0] & [0] \\ [0] & [K_{\Omega_B}^{(e)}]_{24 \times 24} & [0] \\ [0] & [0] & [0]_{24 \times 24} \end{bmatrix}_{72 \times 72}$$



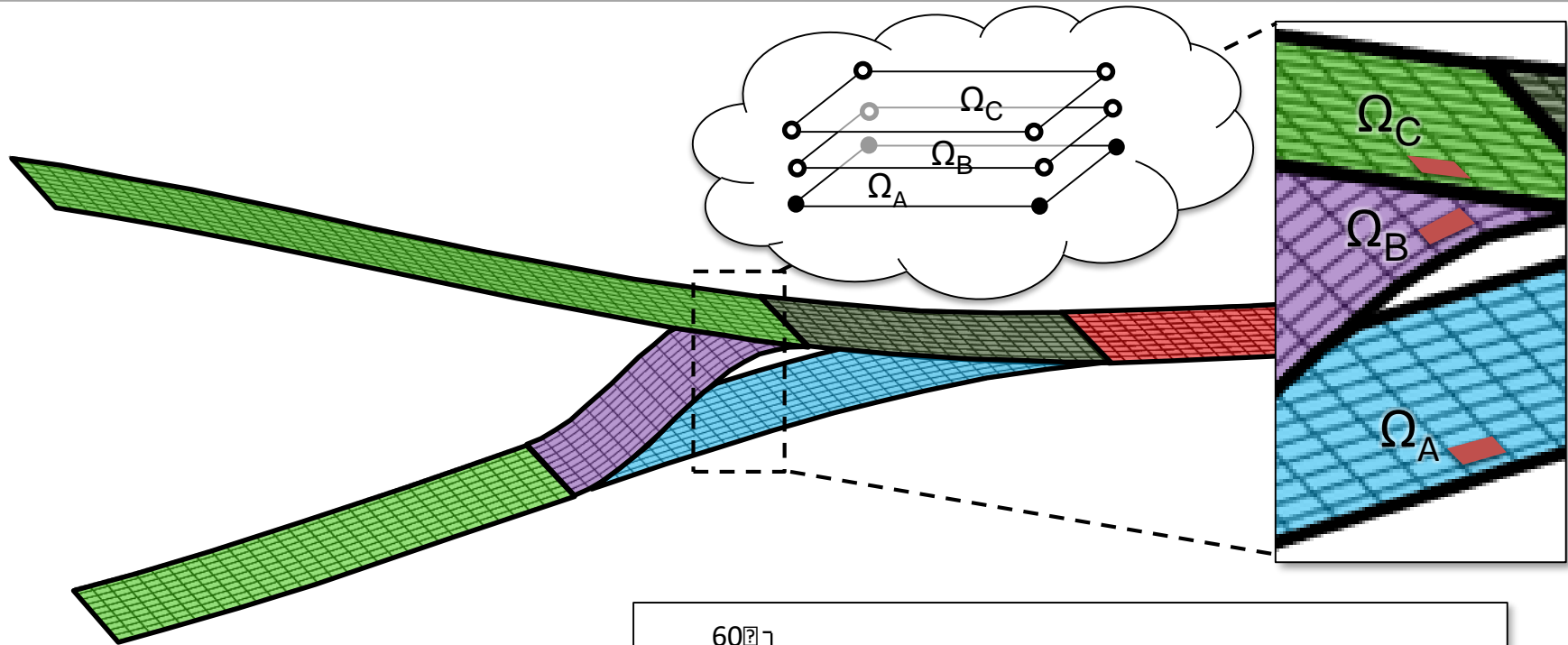
$$K^{(e)} = \begin{bmatrix} [K_{\Omega_A}^{(e)}]_{24 \times 24} & [0] & [0] \\ [0] & [K_{\Omega_B}^{(e)}]_{24 \times 24} & [0] \\ [0] & [0] & [K_{\Omega_C}^{(e)}]_{24 \times 24} \end{bmatrix}_{72 \times 72}$$

○ = floating node (FN)


● = real node (RN)


◐ = RN and unused FN


Ongoing Work: Multiple Delaminations





Number of plies

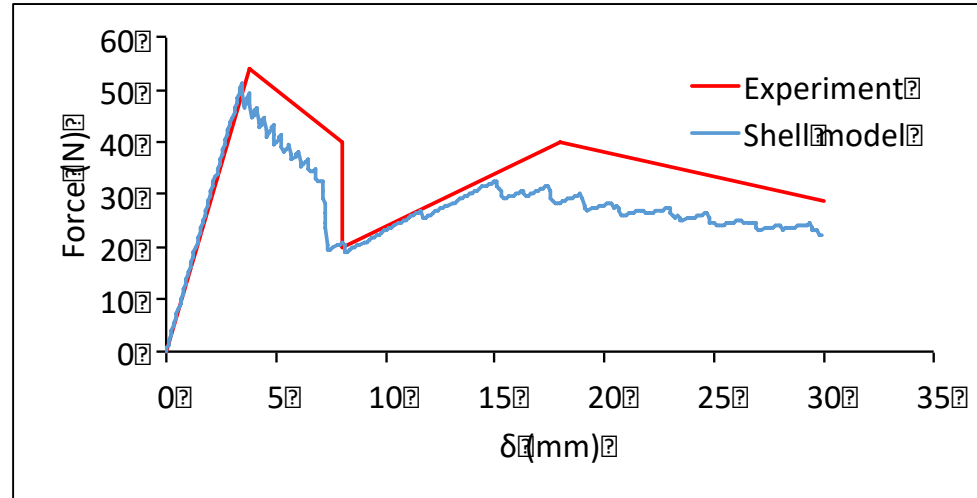
 = 2

 = 10

 = 12

 = 14

 = 24



Ongoing Work: Other



1. Damage initiation
 - Advanced laminate theories (Zig Zag)
 - Stress recovery
2. Code efficiency and robustness
3. Impact simulation
 - Dynamic behavior
 - Explicit solver
4. Alternate Interface
 - Independent solver (decouple from Abaqus)
 - Create Abaqus plug-in
5. Additional failure modes
 - Fiber breakage
 - Fiber kinking
6. Trade study
 - Testing
 - Quantify enhanced efficiency
 - Develop best practices



Concluding Remarks

- AF-Shell: shell element enrichment that allows for efficient damage simulation in composite laminates
- Initial verification and validation complete
- Software development is ongoing via NASA-organized collaboration
- Main areas of needed and ongoing development
 - Application and Testing
 - Contact
 - Multiple delaminations
 - Other: damage initiation, code improvements, impact dynamics, alternate interface, additional failure modes, trade study



QUESTIONS

Mack McElroy
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mark.w.mcelroy@nasa.gov

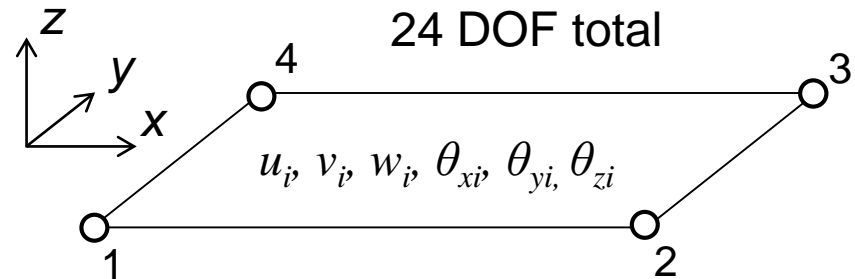


BACK UP

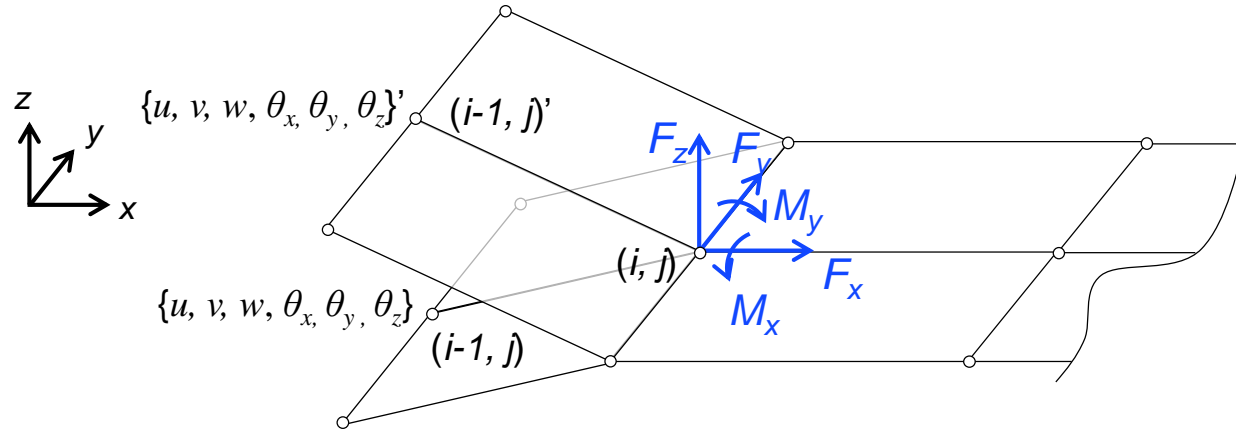
Baseline Element Formulation

Mindlin Composite Shell Element

- Four nodes, 6 DOF per node
- Linear shape functions
- Orthotropic material
- Transverse shear deformable
- Composite section: Classical laminate theory
- Shear locking: full integration w/assumed linear transverse shear strain distribution
- Behaves well for thick and thin shells
- Coded into an Abaqus® 6.14/Standard User Element Subroutine (UEL)



Virtual Crack Closure Technique (VCCT)



Energy release rate equations
for shells [Wang]
(example: propagation in +x direction)

$$G_I^{(+x)} = \frac{-1}{2\Delta A^{(e)}} \left[F_z^{(i,j)} (w^{(i-1,j)'} - w^{(i-1,j)}) + M_x^{(i,j)} (\theta_x^{(i-1,j)'} - \theta_x^{(i-1,j)}) + M_y^{(i,j)} (\theta_y^{(i-1,j)'} - \theta_y^{(i-1,j)}) \right]$$

$$G_{II}^{(+x)} = \frac{-1}{2\Delta A^{(e)}} \left[F_x^{(i,j)} (u^{(i-1,j)'} - u^{(i-1,j)}) \right]$$

$$G_T^{(+x)} = G_I^{(+x)} + G_{II}^{(+x)}$$

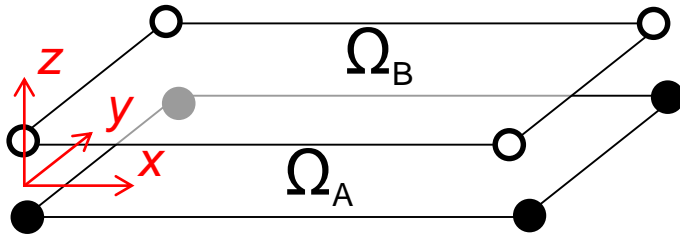
Mixed-mode critical energy
release rate [Benzeggagh], G_c

$$G_c^{(+x)} = G_{Ic} + (G_{IIc} - G_{Ic}) \left(G_{II}^{(+x)} / G_T^{(+x)} \right)^\eta$$

Wang, J.T., and Raju, I.S. "Strain energy release rate formulae for skin-stiffener debond modeled with plate elements." *Engineering Fracture Mechanics* 54.2 (1996): 211-228.

Benzeggagh, M.L., M. Kenane. 1996. "Measurement of Mixed-Mode Delamination Fracture Toughness of Unidirectional Glass/Epoxy Composites with Mixed-Mode Bending Apparatus," *Composites Science and Technology*, 56(4):439-449.

Floating Node Method



Laminate shell element stiffness integration

$$K^{(e)} = \int_b \int_b H^T \left[\int_{-\frac{h}{2}}^{\frac{h}{2}} C(A, B, D, G) dz \right] H dy dx$$

$$A = \int_{-\frac{h}{2}}^{\frac{h}{2}} C_p dz, \quad B = \int_{-\frac{h}{2}}^{\frac{h}{2}} z C_p dz, \quad D = \int_{-\frac{h}{2}}^{\frac{h}{2}} z^2 C_p dz, \quad G = \int_{-\frac{h}{2}}^{\frac{h}{2}} C_s dz$$

split z-integration limits about discontinuity location, z'

Two integration domains

$$K_{\Omega_A}^{(e)} = \iint_{A^{(e)}} H_{\Omega_A}^T \left[\int_{-h/2}^{z'} C(A, B, D, G)_{\Omega_A} dz \right] H_{\Omega_A} dA$$

$$K_{\Omega_B}^{(e)} = \iint_{A^{(e)}} H_{\Omega_B}^T \left[\int_{z'}^{h/2} C(A, B, D, G)_{\Omega_B} dz \right] H_{\Omega_B} dA$$



$$K^{(e)} = K_{\Omega_A}^{(e)} + K_{\Omega_B}^{(e)}$$



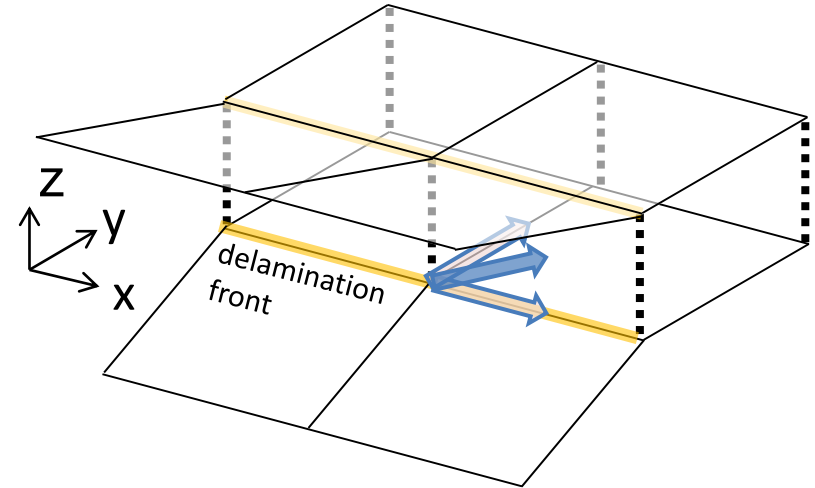
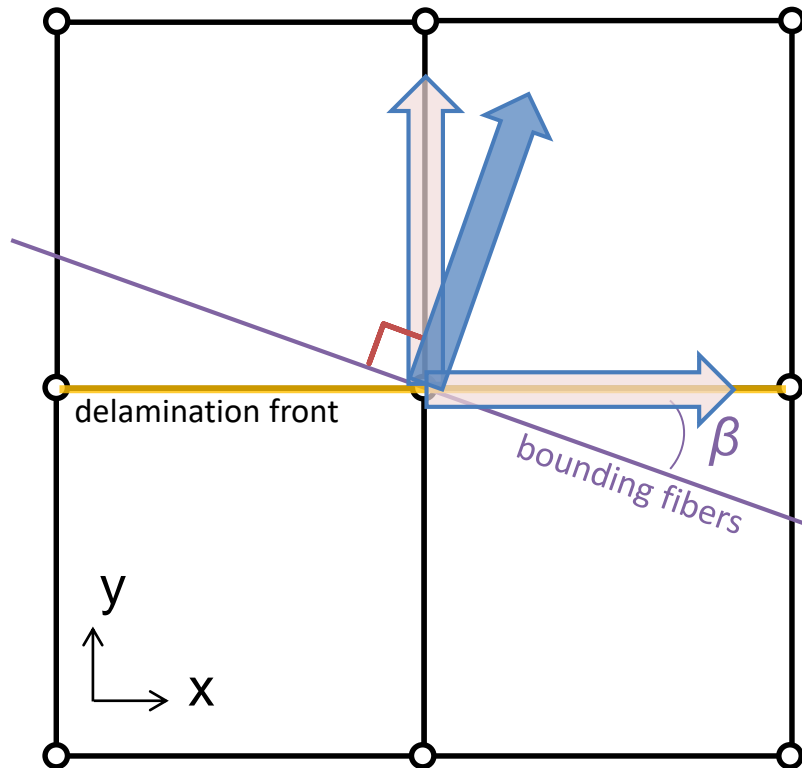
$$K^{(e)} = \begin{bmatrix} [K_{\Omega_A}^{(e)}]_{24 \times 24} & [0] \\ [0] & [K_{\Omega_B}^{(e)}]_{24 \times 24} \end{bmatrix}_{48 \times 48}$$

○ = floating node (FN)

● = real node (RN)

Predicting Transverse Cracks

Assumption: $G^{(mig)}$ is associated with delamination growth perpendicular to bounding fibers

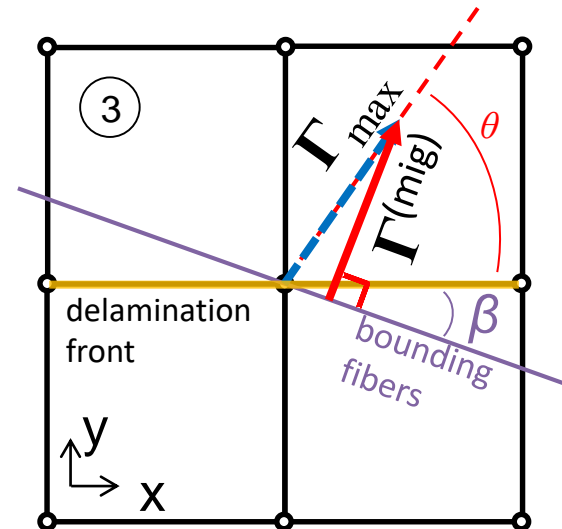
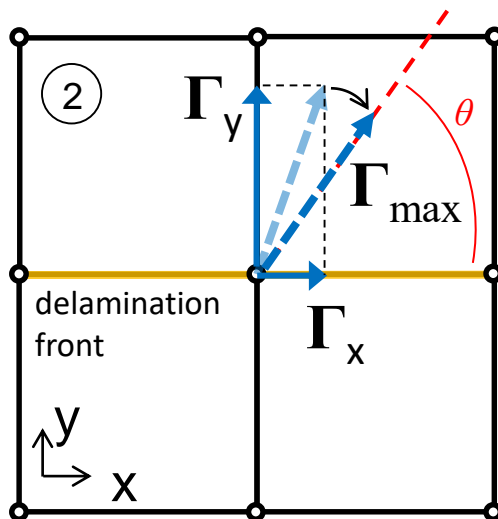
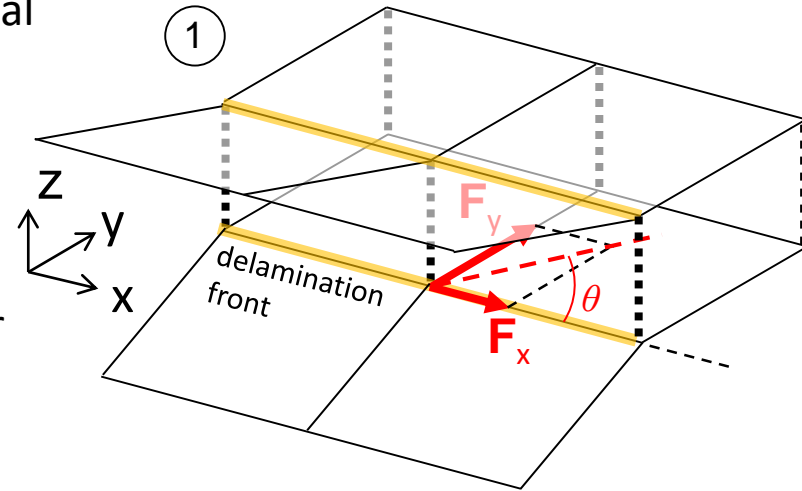


delamination growth directions considered with VCCT $\left. \vphantom{\begin{matrix} \text{delamination growth} \\ \text{directions considered} \\ \text{with VCCT} \end{matrix}} \right\} G_{IIx} \text{ and } G_{IIy}$

delamination growth perpendicular to bounding fibers $\left. \vphantom{\begin{matrix} \text{delamination growth} \\ \text{perpendicular to} \\ \text{bounding fibers} \end{matrix}} \right\} G^{(mig)}$

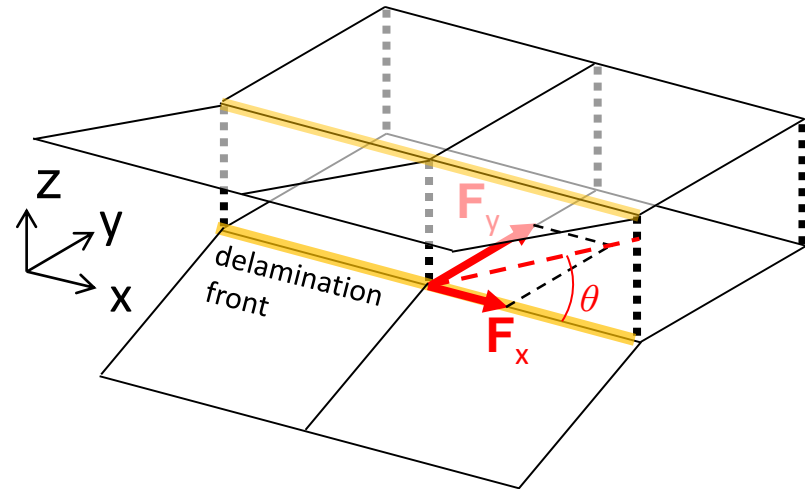
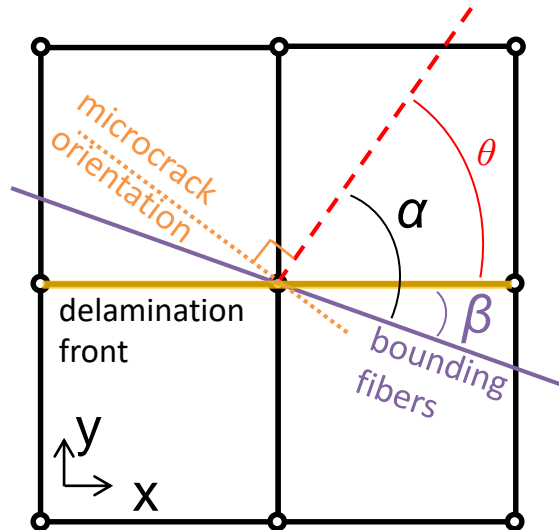
Predicting Transverse Cracks

- ① In-plane shear force vector sum = global growth direction
- ② $|\Gamma_x| = G_{llx}$ & $|\Gamma_y| = G_{lly}$
 $\Gamma_{\max} = \Gamma_x + \Gamma_y$ (analogous to G_{\max})
- ③ $\Gamma^{(\text{mig})}$ is Γ_{\max} component perpendicular to bounding fibers
- ④ $G^{(\text{mig})} = |\Gamma^{(\text{mig})}|$



Predicting Transverse Cracks

Step III: Relative angle between shear vector and bounding fibers

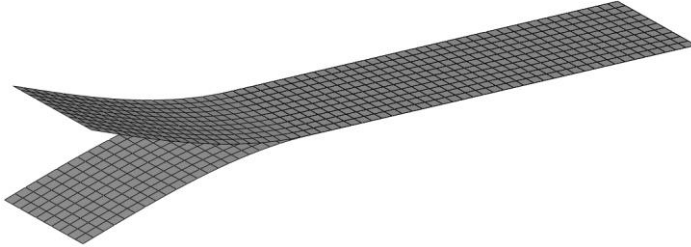


Conditions for a transverse crack:

$$G^{(mig)} \geq G_c^{(tr)} \text{ AND } \alpha \geq \alpha_c$$

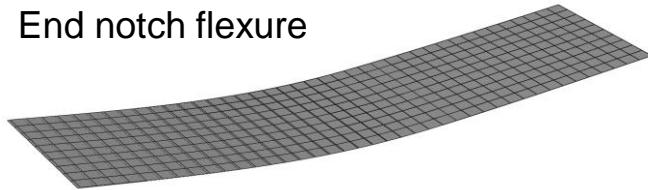
Computational Efficiency

Double cantilever beam

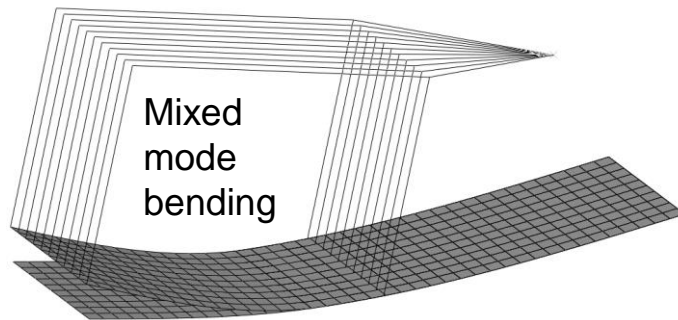


	<u>Mesh size</u>	<u>Runtime</u>
AFS	1.0 mm	37 minutes
	2.5 mm	6 minutes
	5.0 mm	1.5 minutes
High fidelity [Krueger]	1.0 mm	31 hours

End notch flexure



	<u>Mesh size</u>	<u>Runtime</u>
AFS	1.0 mm	34 minutes
	2.0 mm	8 minutes
	5.0 mm	1.5 minutes

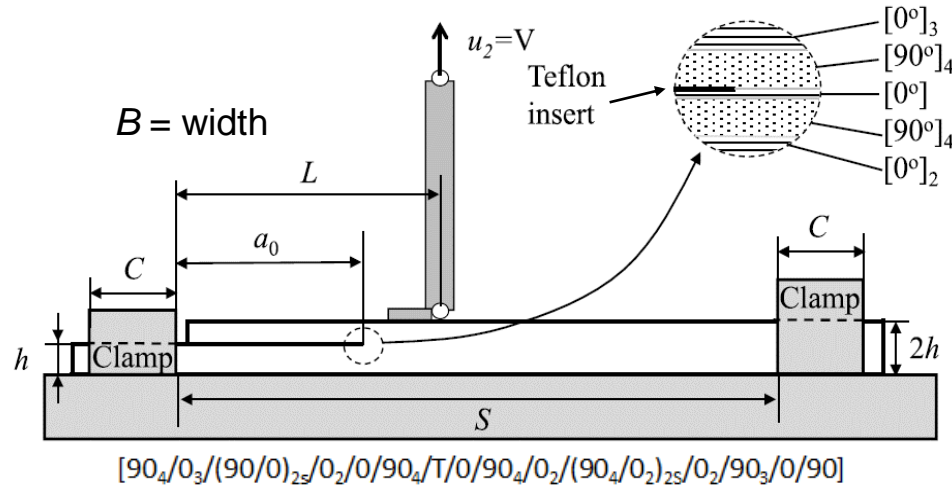


	<u>Mesh size</u>	<u>Runtime</u>
AFS	1.0 mm	50 minutes
	2.5 mm	8.5 minutes
	5.0 mm	1.5 minutes

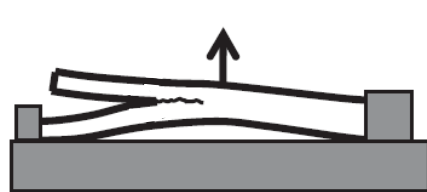
Note: All analyses use 1 CPU

Delamination-Migration Test

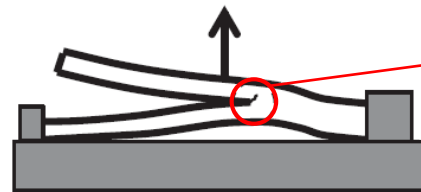
Delamination-migration experiment [Ratcliffe, De Carvalho]



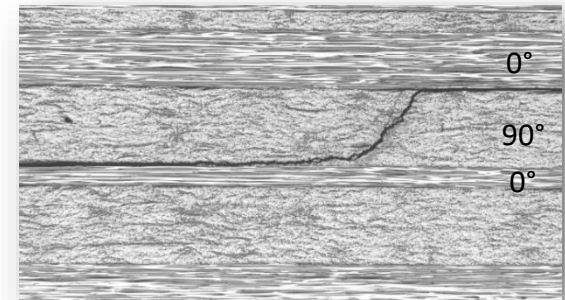
Dimensions (mm)				
B	$2h$	C	S	a_0
12.7	5.25	12.7	115	49



1. Delamination growth



2. Migration

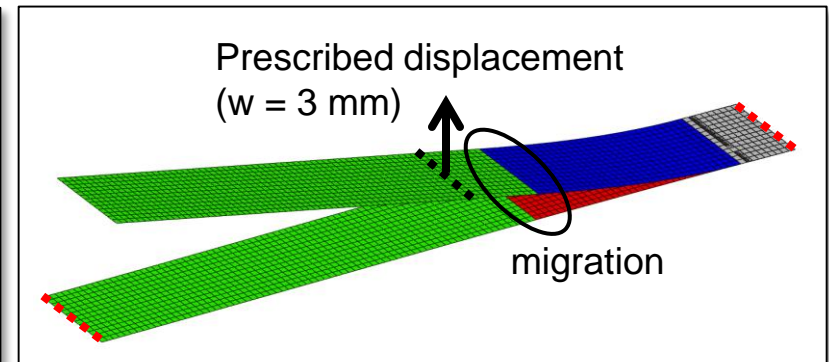
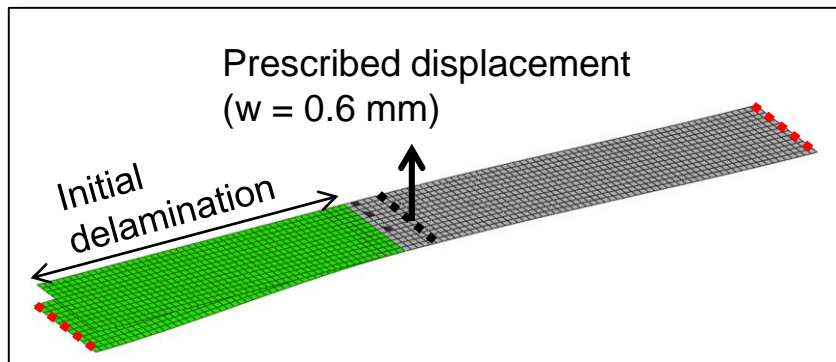
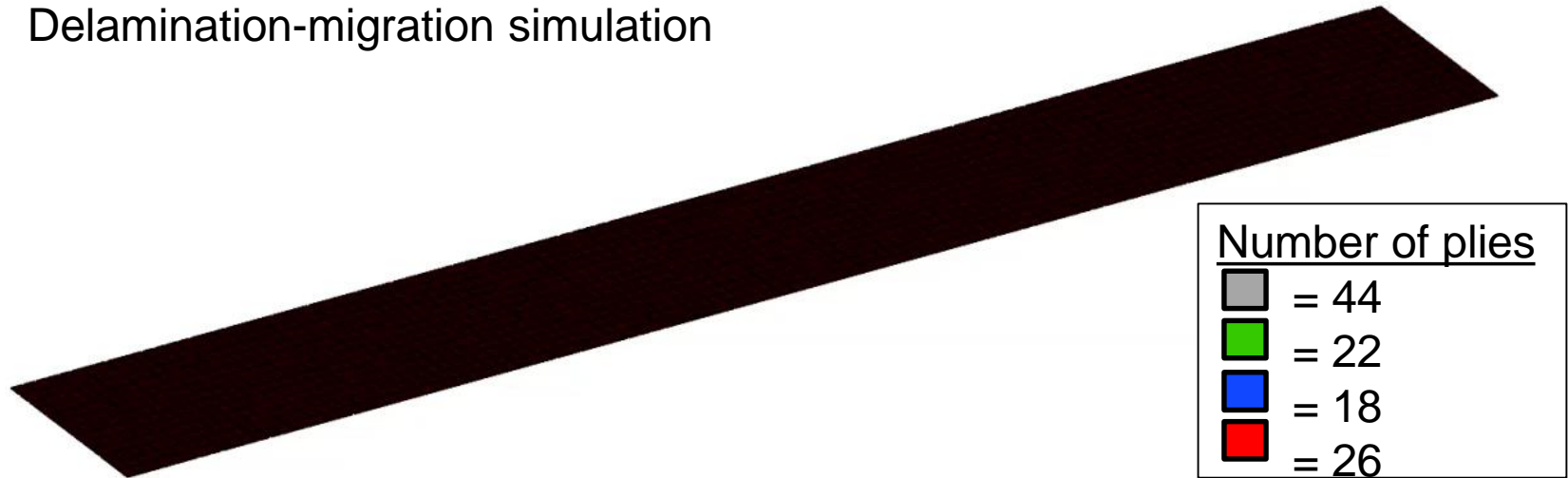


Ratcliffe, J., Czabaj, M., O'Brien, T.K. A test for characterizing delamination migration in carbon/epoxy tape laminates. 2013. NASA/TM-2013-218028.

De Carvalho, N.V., Chen, B.Y., Pinho, S.T., Ratcliffe, J.G., Baiz, P.M., Tay, T.E. 2015. "Modeling delamination migration in cross-ply tape laminates," *Composites: Part A* 71:192-203.

Delamination-Migration Simulation

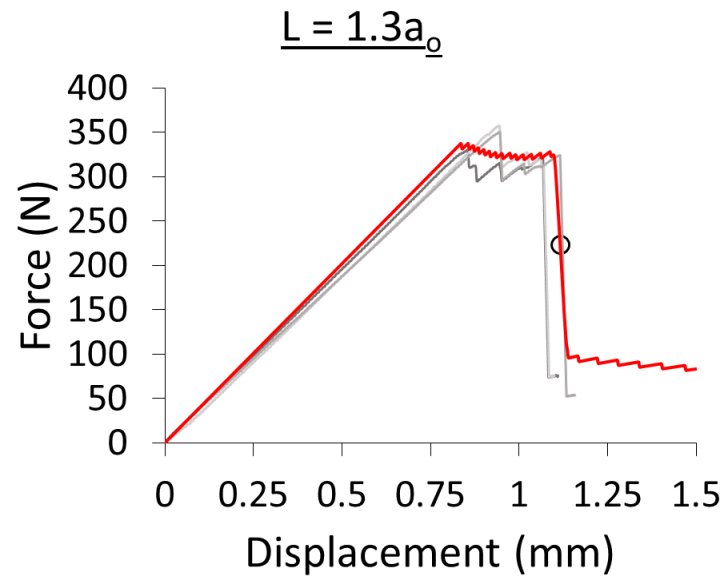
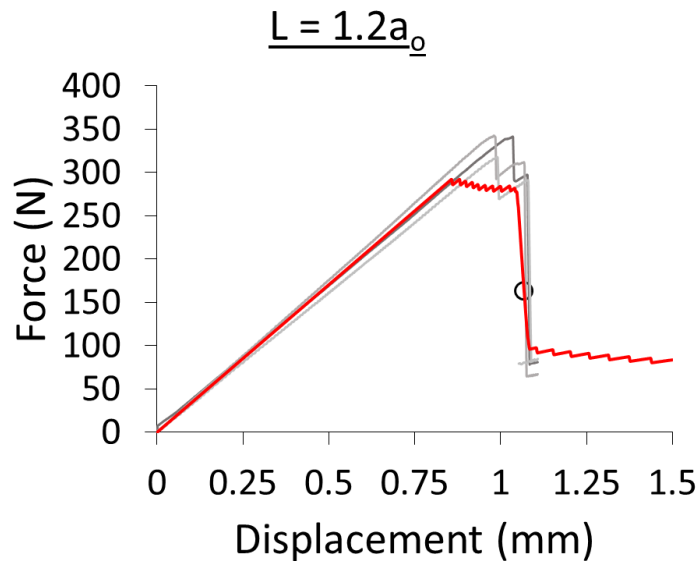
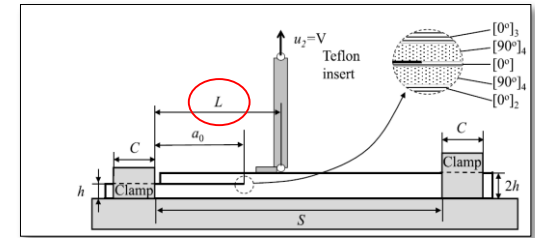
Delamination-migration simulation



..... = Rotational springs

Delamination-Migration Simulation

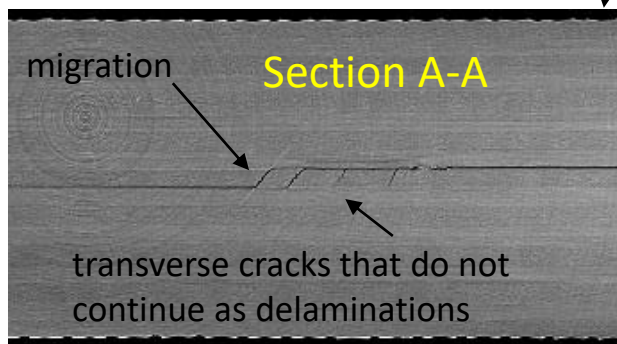
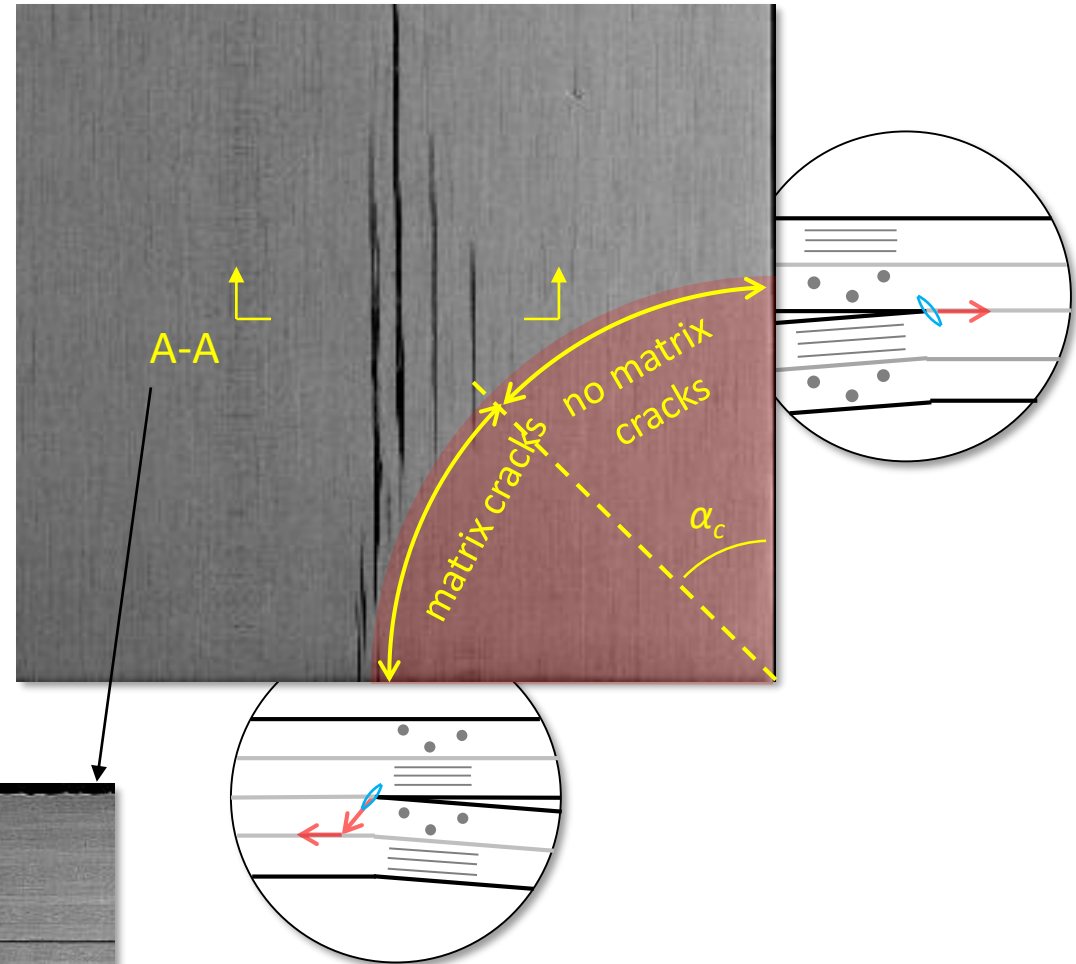
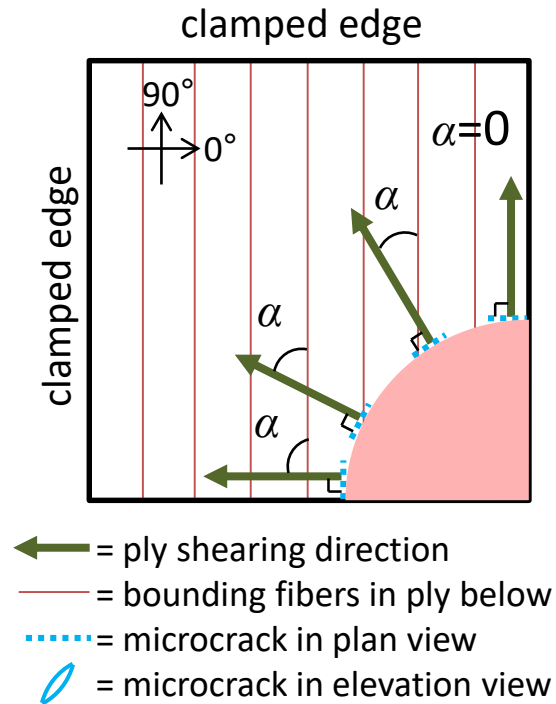
Force-displacement comparison to experiments:



— = Enriched shell model
 ● = Migration

— = Test 1
 — = Test 2
 — = Test 3

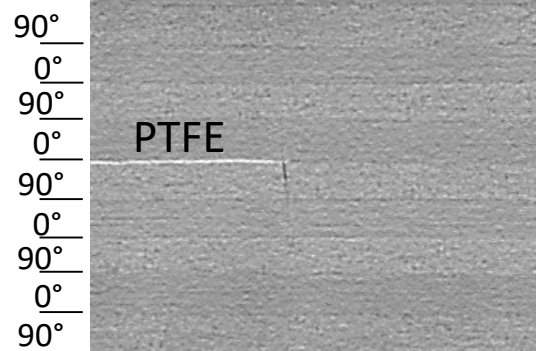
Test Results BBT-1 Detail



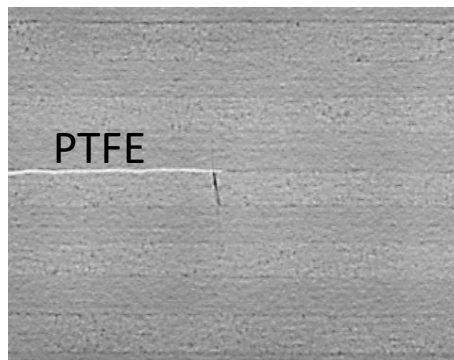
Test Results BBT-1 Detail



pre-delamination *i*:
matrix crack partially
through ply block



pre-delamination *iii*:
matrix crack fully
through ply block



load 1: migration
complete

